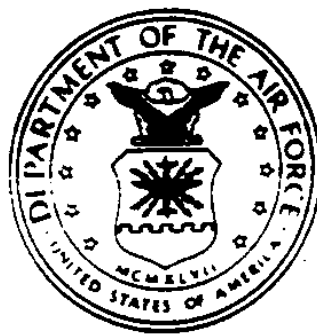
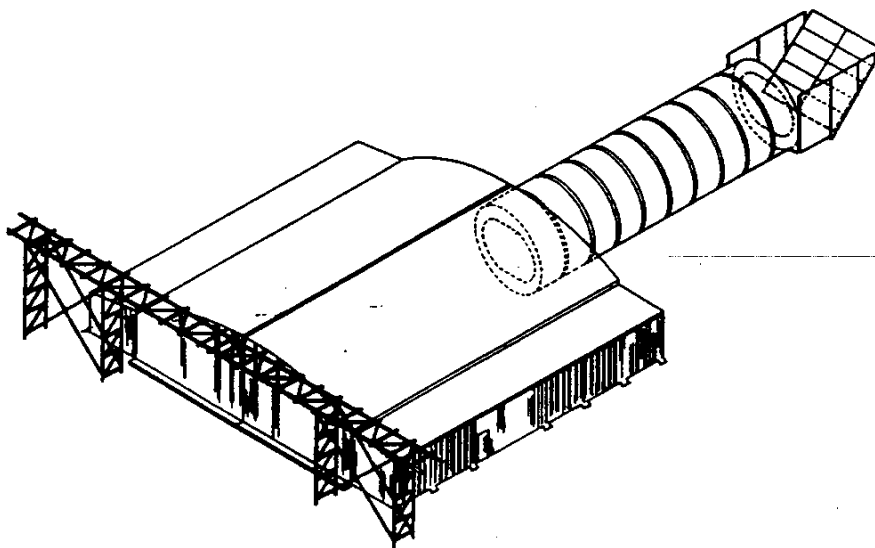


HUSH HOUSE SITE PLANNING BULLETIN



BASE
COMPREHENSIVE
PLANNING



HQ AFLC/DEP and
HQ USAF/LEEVX
1 October 1987

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Base Comprehensive Planning

HQ AFLC/DEP and HQUSAF/LEEVX
1 October 1987

Prepared by
Air Force Logistics Command
Oak Ridge National Laboratory
Boston College



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This report is authored by Alan Witten, Clay Easterly and Robert Miller of the Oak Ridge National Laboratory; Martin Lessen, consulting engineer, Rochester, New York; Monica Swihart of the University of Tennessee, and James T. Beaupre and Francis A. Crowley of Boston College. Volume I of this report is a revised version of earlier siting guidance prepared by Roger Blevins, HQ AFLC/DEPR.

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PREFACE

Base Comprehensive Planning for hush house type jet engine noise suppression test facilities requires consideration of three basic constraints:

1. low-frequency induced vibrations,
2. noise,
3. air quality.

These three factors must be considered together with convenience factors and other land use plans for the optimal siting of hush houses or the siting of other facilities which could be impacted by noise, vibration or air quality around a hush house. This is a multipurpose document, presented in three volumes, developed to assist community planners, architects, engineers, and environmental specialists. While the primary intent of this report is to provide guidance and supporting information for siting, it also provides current baseline information and analyses which can be used in assessing impacts (noise, vibration, and air quality) of hush house operations and establishing construction practices for facilities which could be impacted by hush house induced vibrations.

Volume I provides specific guidance for the siting of hush houses or facilities near hush houses. The information provided in this volume is, in general, non-technical and formatted for use by community planners. Volume I is a revised version of earlier guidance [Base Comprehensive Planning (BCP), Site Planning for Hush House Sound Suppressors, Interim Guidance (Draft), HQ AFLC/DEP, 1984] and reflects the most recent available data and analyses.

Volume II is an in-depth and technical analyses of the three issues (noise, vibration and air quality) which constrain hush house siting. This

volume provides technical support for Volume I and can be used as a reference document for EIAP hush house related issues. This document is intended for use by engineers and environmental specialists.

Volume III documents the data and findings from acoustic studies conducted at two operational hush houses. The study is directed towards quantifying the hush house as an acoustic source. The information provided in this volume supports analyses presented in Vol. II and serves as a basis for future scientific studies. This volume is intended for use by scientists and engineers.

VOLUME II:

HUSH HOUSE SITE

PLANNING

GUIDANCE

Roger Blevins

HQ AFLC/DEPR
Wright-Patterson Air Force Base,
Ohio

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HUSH HOUSE PLANNING GUIDANCE

1. GENERAL INFORMATION

Planning criteria for aircraft turbine engine test stand and noise suppressor test cell facilities is required to support the Air Force Sound Suppressor Program.

This guidance provides information and data for siting jet engine/aircraft hush house noise suppressors and for siting facilities proximate to hush houses. It provides information for selecting the most compatible site with the least possible conflict with noncompatible land uses and facilities. This is supplemental guidance to AFR 864, Base Comprehensive Planning; AFM 19-10, Planning in the Noise Environment; AFR 161-35, Hazardous Noise Exposure; and AFAMRL Reports. It is addressed to all Air Force activities concerned with planning, designing, and constructing jet engine noise suppressor (hush house) facilities.

1.1 Need for Siting Criteria

There are currently more than 70 operational hush houses and additional units are scheduled for completion in the near future. Serious siting problems have been reported at several installations with operational hush houses. The worst of these is the abandonment of an avionics laboratory as a result of vibrations induced in this facility by hush house operations. Land use conflicts could arise as a result of either hush house siting or siting facilities near a hush house. To avoid such conflicts, hush houses should be co-located within the flight zone for organizational efficiency and within the constraints imposed by noise, vibration and air quality impacts. This guidance identifies siting procedures, and criteria design considerations and environmental impact analysis methods for hush houses.

1.2 Scope of Guidance

Facilities are required to test turboprop or turbojet engines before or after maintenance or repair and prior to installation on aircraft to ensure that no problems were introduced or remain uncorrected. This requirement prevents the installation of engines in the aircraft which require further maintenance. Facilities of this type include bare engine test stands, test cell noise suppressors, and hush house noise suppressor. This material provides site location guidance which can be used for both turbine hush house noise suppressor facilities and facilities surrounding hush houses. Additional siting criteria on noise constraints is in AFM 19-10. Base Comprehensive Planning requirements is provided in AFR 86-4. Environmental assessments should be provided in accordance with AFR 19-1, AFR 19-2, and NEPA. Noise exposure standards are provided in AFR 16135.

1.3 Responsibilities

The MAJCOM and base components responsible for planning, designing, and construction of airfield mission support facilities should utilize the basic criteria of this document. The MAJCOMs may supplement or amplify this material because unique operational aspects of an individual mission are not covered in this publication.

1.4 Facilities and Equipment Nomenclature

Facilities and equipment in this document may be referred to as turboprop, turbojet or turbofan engine and suppressor/noise suppressors, or hush houses. The designs may differ among manufacturers and application or use. For site location purposes there are hush house sound/noise suppressors (hangar and semihangar). This document is directed to the current fighter type aircraft (AF37/T-10 or AF37/T-II) hush house and large engine hush house (AF32/T-9).

2. TURBINE ENGINE TEST FACILITIES

2.1 Turbine Engine Test Facilities

Turbine engine test facilities include bare engine test stands, test cells and a variety of enclosed aircraft/engine noise suppressors. The scope of this guidance is limited to three types of aircraft/engine noise suppressors. These are the T-9, T-10, and T-11 (a T-10 wired for European current) hush houses. Special guidance is provided for these three types of facilities because (1) they are relatively new, representing the state-of-the-art in engine/aircraft test facilities, (2) the Air Force is committed to the deployment of the facilities, and (3) these type of facilities pose unique challenges to both their optimal siting and the siting of surrounding facilities.

2.1.1 Enclosed Aircraft/Engine Noise Suppressor (Hush House)

This hanger-type facility is designed to support fighter aircraft (Fig. 2-1). It is constructed of prefabricated sheet steel and fiberglass panels. The structure is erected over a concrete pad and provide with utility service. This type of hush house can accommodate either a bare engine mounted on a test stand (Figs. 2-2, 2-3) or installed in an aircraft (Fig. 2-4). The sidewalls of the structure are composed of acoustic baffles designed to allow airflow into the building and attenuate sound leaving the building. Air enters the interior of the building through five air inlet doors on each interior sidewall. Air entering through the four doors forward of the control and equipment rooms is drawn into the engine air inlet. Air passing through the six rear sidewall inlet doors is entrained by the flow of engine exhaust gas as it enters the augmentor tube. This air can mix with the exhaust gas to reduce its temperature as it moves through the augmentor tube. The augmentor tube is the conduit through which exhaust gas exits the

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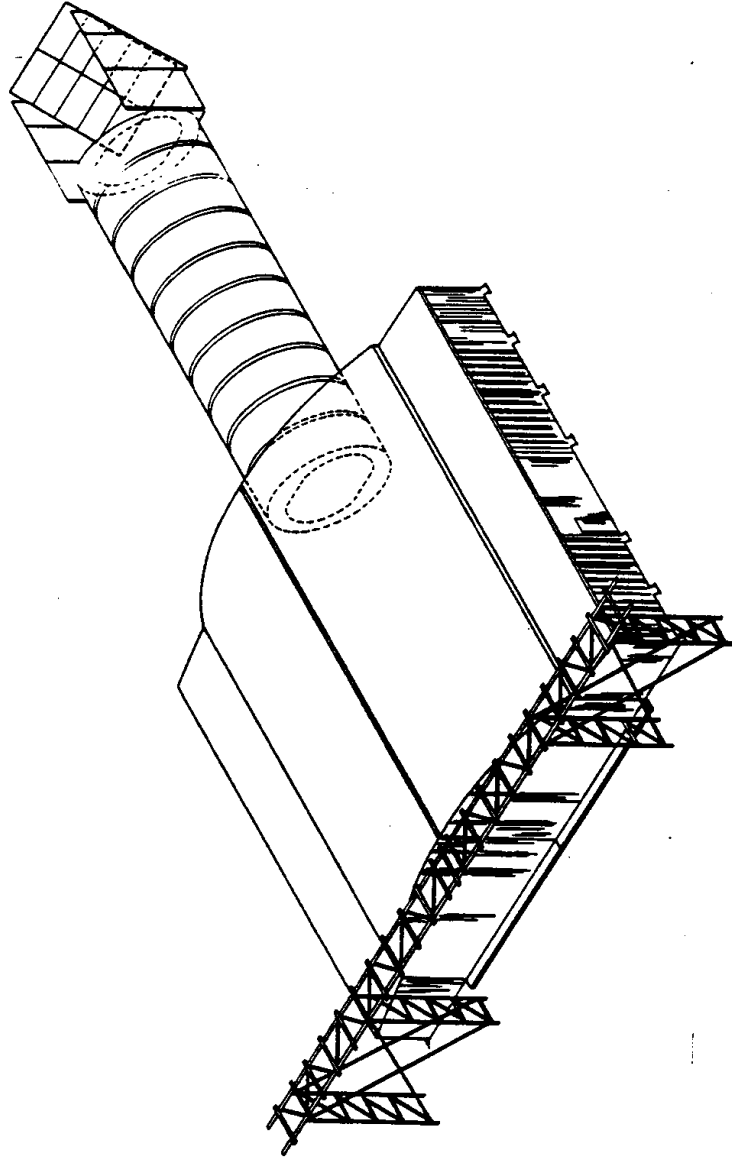


Figure 2-1. Sketch of a T-10 hush house.

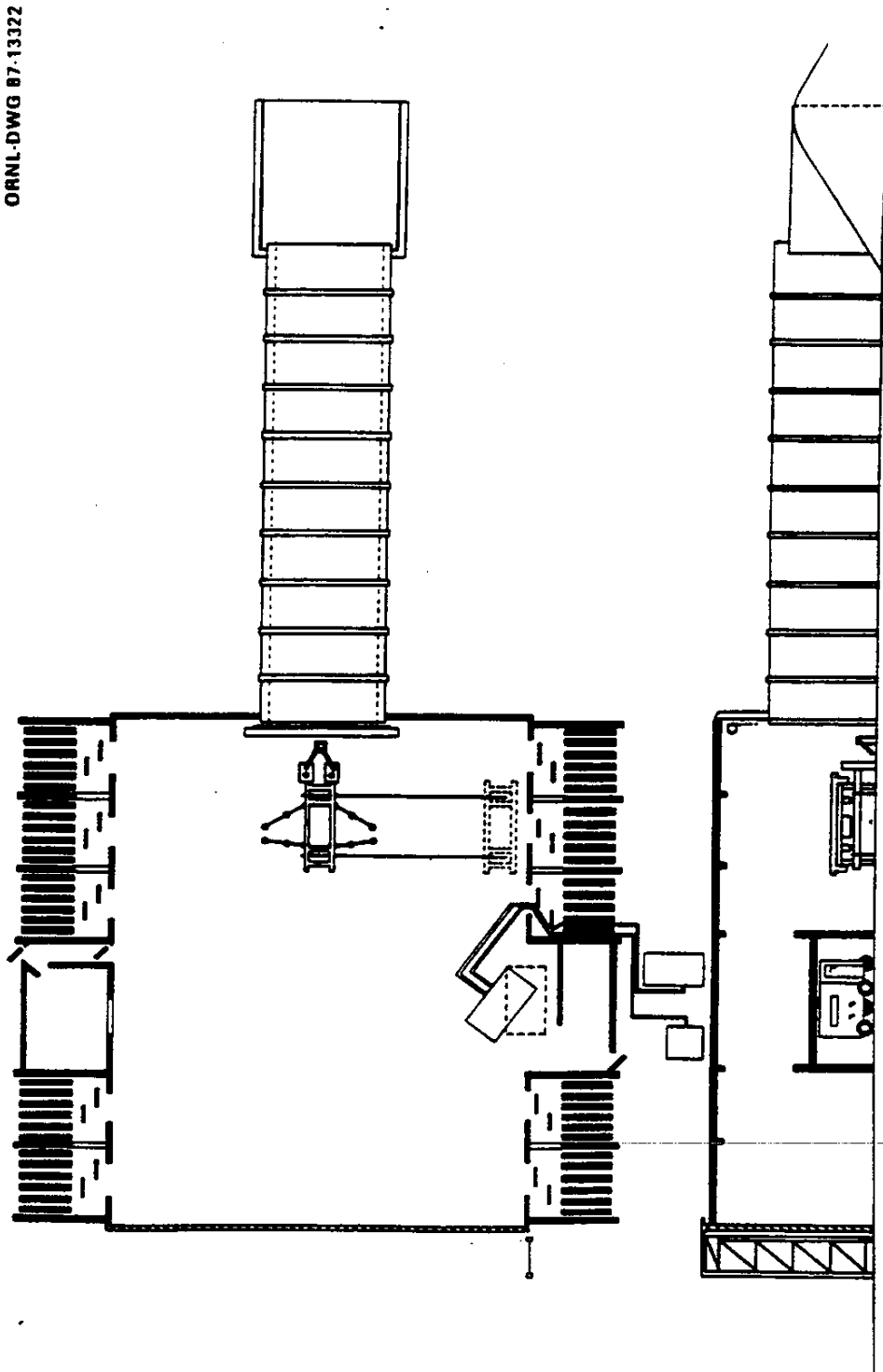


Figure 2-2. Cross-sections of a T-10 hush house configured for bare engine testing.

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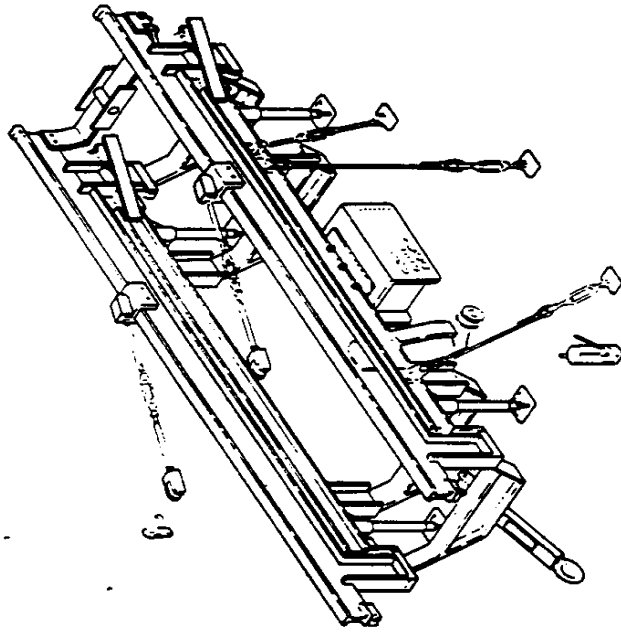


Figure 2-3. Test stand used for bare engine testing in an T-10 hush house.

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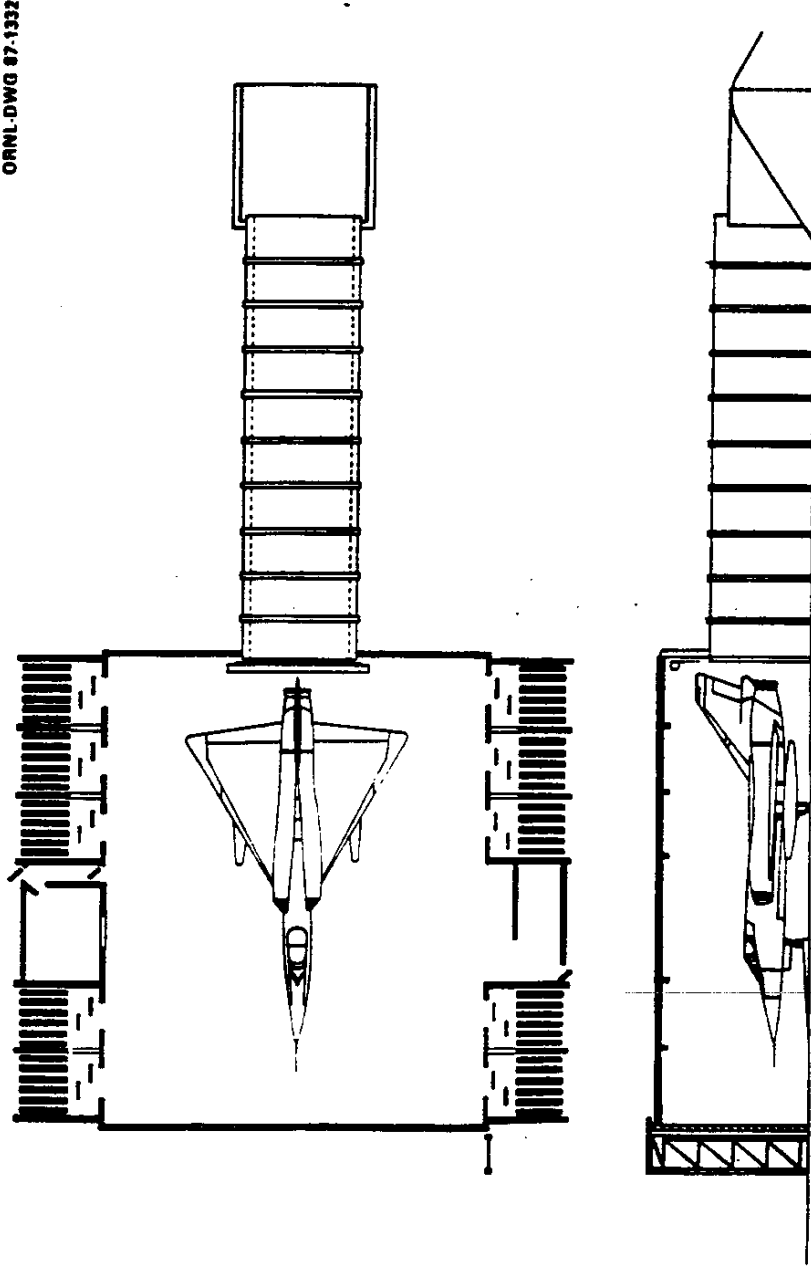


Figure 2-4. Cross-sections of a T-10 hush house configured for installed (in an F-106) engine testing.

hush house. It is 79 ft long, oval in cross-section, and terminates at a 45° ramp deflector which imparts a vertical component to exhaust. The front doors of the hush house are filled with sound absorbing material. In order to minimize both thermal stress on the walls of the augmentor tube and engine backpressure, it is important to achieve close alignment of the axes of the engine and augmentor. The hush house A/F 37T-10 and the A/F 37T-II (an A/F 37T-10 wired for European current) is semi-permanent equipment designed to be disassembled and mobilized. The category code for hush house facilities is 211-193.

2.1.2 Large Turbojet/Turbofan Engine Enclosed Noise Suppressor System (Hush House)

The large engine hush house is an air cooled system, designed to handle high volume air flow, large thrust, and high temperatures while abating noise (Fig. 2-5). This system is frequently referred to as the T-9 hush house and is used to test large jet engines such as the CFM56 or F101-GE-102. These facilities are designed for the operation of bare engines only, with the engine suspended from above in a manner similar to its mounting below a wing. The sidewalls of the T-9 hush house are solid. Air enters the building through open acoustic baffles above the front doors and through the rear wall beside the front on the augmentor tube. Air entering through the front is drawn into the engine while air entering through the rear is entrained by the engine exhaust flow in the augmentor tube. The T-9 augmentor tube is identical to that for the T-10 (Sect. 2.1.1) but terminates at a steeper deflector made up of an array of turning vanes. The hush house A/F 32T9 is semi-permanent equipment designed to be disassembled and mobilized. The category code for hush house facilities is 211-193.

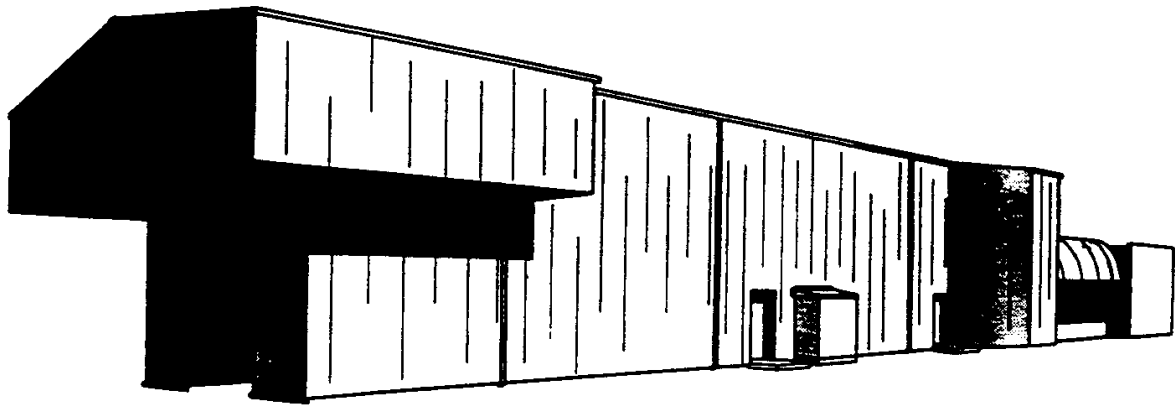


Figure 2-5. Sketch of a T-9 hush house.

2.2 Foundation Systems for Turbine (Jet) Engine Test Facilities)

The purpose of this report is not to specify foundation design. In a survey of operational hush houses (Vol. II, Sect. 3.4), no hush house foundation problems were identified.

Following is general guidance for the development of hush house foundations. Detailed foundation engineering and design information can be found in AFM 88-15 and other appropriate design documents.

2.2.1 Conventional Pier and Grade Beam System

Wooden piers are driven or concrete piers poured to a prescribed depth and a series of beams support the hush house. The system is particularly useful where soil is loam or clay.

2.2.2. Floating Slab

The concrete pad is precisely poured over a prepared site without the need for special supports. A floating slab foundation is feasible where soil conditions are extremely good.

2.2.3 Spread Footings

There are cast in place concrete beams poured on previously cast footers which are wider than the beams. This extra width spreads the load over a wider area to keep the unit soil load within acceptable limits for the local soil characteristics.

2.2.4 Special Design

Problem sites or soils may require foundation systems not discussed. Design and construction costs should be expected to be above normal limits.

3. SITE PLANNING GUIDANCE FOR HUSH HOUSE TEST FACILITIES

3.1 General Information

3.1.1 Background Information

This section provides a procedure for estimating the T-9, T-10, and T-11 hush house facility clearances based on known noise and vibration levels and air quality. Tables are provided to estimate the minimum distances from a sound suppressor/hush house to ensure a reasonable communications and work environment.

3.1.2 Site Location Suitability

The information provided in this chapter is to mitigate location conflicts. The desired result is to achieve the best practical, economical, and functional location for all land uses and activities, fitted to the natural environment and the existing airfield land use patterns and articulated with the aircraft and jet engine maintenance operations. These standards are not absolutes but should serve as guidance to be used under normal or average operations.

3.2 Site Planning Guidance

3.2.1 Convenience Requirements

The aircraft maintenance complex, which includes enclosed areas for maintenance and shops, requires co-location for organization and functional efficiency. The jet engine hush house facilities should be located near or within a reasonable towing distance to the maintenance complex. Aircraft jet engines mounted on a tow trailer and towed for excessive distances are exposed to seal damage and foreign object damage.

(1) Maximize Access to User. The jet engine maintenance (MA) community is the principal user and operator of hush houses. To best meet MA needs, the hush house should be near repair, overhaul or maintenance facilities.

The location should prevent long towing or taxiing distances, crossing active runways and movement on parallel taxiways.

(a) Jet engines are generally towed at ten miles an hour. Excessive distances from the overhaul facility may incur excessive labor in the movement of aircraft engines.

(b) The roadway or taxiway between test site and overhaul site should be smooth and relatively free of rough pavement.

(2) Minimum Separation Distance from Jet Engine Maintenance Facilities. There are no specified distances between the hush house and jet engine maintenance facilities. Unsuppressed test stands have been traditionally sited three to five miles from the flight line or cantonment area. The preferred location of hush houses is directly adjacent to the Jet Engine Intermediate Maintenance (JEIM) or Inspection and Repair (I&R) shop. An acceptable separation would be up to one mile. Any greater separation should be carefully reviewed with the user.

Convenience standards are based on efficiency, economics and organizational preference.

3.2.2 Performance Standards

The performance standards provide criteria to be used in evaluating the acceptability of a location based on the degree of noise and vibration hazards and airborne emissions. This procedure emphasizes the use of technology and engineering data to achieve technical standards of performance for the location of a hush house sound suppressor facility. Through the comparison of hush house operational characteristics and location constraints the site selection process may become more precise. Sites for hush houses should be selected to least affect land uses or functions sensitive to noise or vibrations.

3.2.3 Site Evaluation Based on Noise

(1) Site evaluation based on noise conditions can be performed by using the following guidance:

(a) AFAMRL-TR-73-110, Community Noise Exposure Resulting from Aircraft Operations: Acoustic Data on Military Aircraft, Volume 1.

(b) AFAMRL-TR-81-148, Far-Field Acoustic Data for the Texas ASE. Inc.. Hush House, April 1982.

(c) AFAMRL-TR-75-50, USAF Bioenvironmental Noise Data Handbook, Volume 172, July 1982.

(d) AFR 61-35, Hazardous Noise Exposure

(e) AFM 19-10, Planning in the Noise Environment.

(f) Base Air Installation Compatible Use Zone (AICUZ) Report.

(g) Volume II, Sect. 3.1.1 of this report.

(2) The following are several paragraphs explaining how to determine the noise impact for siting any Air Force equipment. This only addresses the question of audible noise and not the low frequency noise problems. Information on the low frequency noise levels for the hush house has been provided by octave band in the Bioenvironmental Noise Data Handbook, AMRL-TR75-50, Volume 172. If finer analyses are required, these could be provided on a case-by-case basis. This information provides only what the acoustic levels will be at any distance and angle from the various Air Force aircraft operating in the hush house at various power settings. It is out of the scope of AFAMRL laboratory's efforts to determine what effect these levels will have on buildings of various construction (Mr. Bob Lee, AFAMRL/BBE).

(a) To site any Air Force equipment that emits audible noise, the effect of this noise on community annoyance, speech interference and telephone conversation must be considered. To evaluate the community

annoyance to audible noise, the applicable metric is the day-night level (L_{dn} or DNL). How to do a hand calculation of the DNL from a group runup operation (i.e., F-16 operating at A/B in the Texas ASE hush house) is explained in detail with examples and worksheets in AFAMRL-TR-73-110, Volume 1, "Community Noise Exposure Resulting from Aircraft Operations: Acoustic Data on Military Aircraft." The input noise characteristics for various Air Force aircraft operating in the Texas ASE hush house is found in the AFAMRL TR-81-148, "Far-Field Acoustic Data for the Texas ASE, Inc., Hush House." These DNL values can then be compared to the compatible land use guidelines in AFM 1910, "Planning in the Noise Environment," to determine acceptability of the selected site with respect to annoyance of people and compared with local and/or state noise related statutes, where applicable to determine compliance.

(b) To examine the question of speech interference and telephone conversation interruption, the AFAMRL-TR-75-SO Bioenvironmental Noise Data Handbook series provided A-weighted sound level, and speech interference levels for all Air Force noise sources at various distances, angles of orientation and power or operational levels. This information can then be compared to Table 3-1 or similar standard charts to determine the extent of interference (i.e., speech difficult at 10 feet, 30 feet, etc.)

(c) With this information a planner at a local base must then make a tradeoff judgment on the impact of the proposed siting, i.e., is the added convenience of putting the hush house SO feet closer worth the difficulty of speech at 20 feet for only one office that has six people in it.

(d) Using the Base Comprehensive Plan (BCP), Existing Facility Tab G1 plot the noise contours onto the tab from the proposed hush house site.

**Table 3-1. Exclusion distances based on human effects for
maximum sound pressure levels.**

Source/Health Effect	Target Noise Level (Outside)	Exclusion Distance* (ft)
Infra-sound (15 Hz) Chronic	95 dB	4000 Assuming no building attenuation
	Acute 120 dB	250 Assuming no building attenuation
Noise (A-weighted) Hearing loss	89 dBA	250 open work area
	100 dBA	200 building (assume 15 dB attenuation)
Speech Interference	80 dBA(assuming 15 dB building attenuation)	800 95% indoor sentence in- telligibility
	65 dBA	4000 95% outdoor sentence in- telligibiltiy at 2 meters raised voice

The HAF/LEE 7115 facility listing or other real estate reports should be consulted to determine the facility land use or function.

(e) An alternative for sites located within the Air Installation Compatible Use Zone (AICUZ) Ldn 75-80 is to assume the noise exposure is already present due to aircraft operations. Unsuppressed jet engine operations may create an audible noise hazard much greater than the hush house in the Ldn 75-80 noise area. A careful review of the Air Installation Compatible Use Zone (AICUZ) contours should assist the site planning.

(3) The AICUZ program is enhanced by the hush house in that it allows aircraft test runs in the flight line area. Table 3-, provides a comparison of representative noise levels for a hush house and the comparable unsuppressed engine runup. As is evident from this table, the hush house served to reduce noise levels by at least 50 dBA. 3.2.4

Site Evaluation Based on Vibrations

Operating hush houses emit acoustic energy in the subaudible frequency range (infrasound). These emissions are sufficient to cause detectable vibrations in walls and windows of nearby buildings and unsecured objects within these buildings.

(1) The issues associated with infrasonic emissions from hush houses relevant to siting concerns are:

(a) Direct human exposure to infrasound or the vibrations it induces,

(b) The prevention or disruption of functions in a vibrating environment,

and

(c) Long-term structural damage resulting from induced structural

vibrations.

**Table 3.2. Noise levels (dBA) at 250 ft for unsuppressed engine runup
(open air), the same engine operating in a hush house (installed)
and the difference between the two (insertion loss).**

<u>Aircraft</u>	<u>Open Air</u>		<u>Installed</u>		<u>Insertion Loss</u>		
	<u>MP¹</u>	<u>AB²</u>	<u>MP¹</u>	<u>AB²</u>	<u>MP¹</u>	<u>AB²</u>	
F-4	123.5	130.6	70.1	79.0	53.4	51.6	
F-15			73.9	79.8			
F-16	122.0	129.3	68.7	73.1	53.3	56.2	
F-105			70.0	76.7			
F-106			68.2	76.3			
F-111F			68.9	79.6			
T-38			77.6	78.5			
B-1			--	88.7			

¹ Military power

² Afterburner

- Data unavailable

(2) Siting criteria associated with hush house induced vibrations are difficult to establish. The study of low-frequency vibration problems has generally been reserved for unique areas such as the space programs. A survey of facilities within operational hush houses (Vol. II, Sect. 3.4) has revealed that vibrational impacts do occur and that these impacts present land use conflicts. Allowable or threshold levels of vibration have been established for the issues cited above.

(a) For human exposure, threshold accelerations guidance can be found in American National Standards Institute (ANSI) Standard S3.291983 Guide to the Evaluation of Human Exposure to Vibration in Buildings

(b) For vibration sensitive functions (PMEL, avionics, etc.), accelerations are to be less than 10^{-3} or 10^{-4} g ($19 - 9.8 \text{ m/s}^2$).

(c) Long-term structural damage may occur for wall accelerations greater than 0.01 g .

Relating the above criteria to siting guidance is difficult because only limited data exist which correlate hush house operations with observed wall accelerations (Battis, 1985; Battis, 1987). The magnitude of induced wall accelerations will depend on the following factors: the type and power setting of the engine being tested in the hush house, the size and construction type of the potentially impacted facility, and the orientation and location of the potentially impacted facility relative to the hush house.

(3) Vibration induced impacts have been assessed (Vol. II, Sect. 3.1.3) on the basis of available vibroacoustic field data, a survey of installations with operational hush houses (Vol. II, Sect. 3.4), and an analysis of the response of a model wall (Vol. II, Appendices A and B). Relevant finds based on available information are:

(a) Vibration-related impacts of hush house operations are expected to be most significant for the testing of pure jet (low bypass) engines operating at military power or with afterburner. Thus, careful siting of a hush house or a facility near a hush house is required for T-10 and T-11 hush houses, and T-9 hush houses which service the F101 (B-1) engine.

(b) No chronic or acute human health impacts are expected. Levels of vibration sufficient to cause human discomfort or annoyance may occur during engine testing in the afterburner mode. Duration and frequency of these tests are typically 20 seconds, several times per day.

(c) Vibration levels will be greatest for multi-story wood frame or pre-engineered structures. Vibration-sensitive functions can be performed without significant risk of interference beyond 500 ft from a hush house for a single-story masonry structure with minimum window and door areas on the exterior wall facing the hush house. The minimum separation distance for a single-story pre-engineered or wood frame structure housing vibration sensitive functions is 2000 ft. Safe separation distances for multi-story structures are at least twice those for single-story facilities.

(d) Administrative functions may be sited somewhat closer to hush houses however, no closer than 500 ft for single-story masonry or 1000 ft for single-story, pre-engineered or other light weight construction. Siting administrative functions at or near minimum separation distances could result in intermittent annoyance during afterburner tests.

3.2.5 Site Evaluation Based on Air Quality

(1) Jet engine test cell emissions are subject to the control and regulation by local, state and federal governments. Local pollution control

boards may require a review of proposed action and reserve regulation for nuisance control or prevent operation to reduce particulate emissions.

(a) Concentrations of pollutants in the ambient air can be somewhat reduced by siting the hush house as far as possible from the nearest fence line and by orienting the exhaust tube to direct pollutants away from the nearest fence line. Note that the benefit is only slight, however, because concentrations that are almost as large as the maximum concentration occur at distances which are well beyond the fence line for varying meteorological conditions (Vol. II, Sect. 3.2).

(b) A related issue concerns whether a hush house would emit pollutants in quantities that exceed a threshold at the source which would qualify the hush house as a major source. If so, it is subject to New Source Review, which contains standards in addition to ambient air quality standards, such as Prevention of Significant Deterioration (PSD) increments or offsets by means of reductions in emissions at existing sources. In general, hush houses are not expected to exceed the source threshold, and therefore the consequences of New Source Review should not be a factor in hush house siting.

(c) Reduction of visibility because of the exhaust plume will not be altered by hush house siting and therefore is not a consideration in the siting process. The exhaust tube should be directed toward an open area, however, so that the plume is not impacting or close to nearby buildings or other structures.

(d) The opacity of the exhaust plume is highly variable as a function of the engine type, ranging from being indistinguishable to being in violation of applicable opacity standards.

(2) The hush house does not use wet packed scrubbers or filters. Particulate emission is determined by the emission characteristics of the aircraft being tested. The only air quality issue which is expected to cause a regulatory conflict is the exhaust plume opacity resulting from particulate emissions. This issue is of concern in California where facilities, in order to satisfy the regulatory agency, have committed to convert to more modern, "cleaner-burning" engines.

(31) The use of pollution control devices does not appear to be a viable option since such devices must be specially designed to ensure proper engine performance, would be costly to construct and operate, and are expected to offer only low pollutant removal efficiency.

(4) Timely consultation with the local regulatory authority to resolve potential air quality permitting conflicts is encouraged. 3.2.6 Integrated Siting Guidance

Siting guidance is provided based upon the existing body of knowledge associated with noise and vibration impacts of hush house operations. Potential for air quality impacts may influence siting and base land use practices; however, air quality issues will be quite site-specific and a function of local ambient air quality and the perspective of the appropriate air quality regulatory agency.

(1) The siting guidance provided reflects the available relevant information. It is important to note that only limited field data are available regarding hush house related vibrational impacts. For this reason, compliance with this guidance does not eliminate the possibility of land use conflicts. It is anticipated; however, that adherence to this guidance will minimize impacts. Refinements to this siting guidance can occur only with the availability of a more extensive vibroacoustic data base.

(2) Siting guidance is provided in the format of inclusionary zones or regions around a hush house. General functions and construction types are suggested within each zone. The area surrounding the hush house is segregated into 6 circular or concentric annular zones. These zones, given at distances from the hush house, are:

- Zone 1 - less than 250 ft
- Zone 2 - 250 to 500 ft
- Zone 3 - 500 to 1000 ft
- Zone 4 - 1000 to 2000 ft
- Zone 5 - 2000 to 3000 ft
- Zone 6 - greater than 3000 ft.

Land uses are segregated into 7 functional groups and 4 construction types
These are:

<u>Functional Groups</u>	<u>Construction Type</u>
Group 1 - aircraft operations and maintenance	single-story masonry
Group 2 - industrial	multi-story masonry
Group 3 - Administrative	single-story light weight
Group 4 - community	multi-story light weight
Group 5 - medical	
Group 6 - housing	
Group 7 - vibration-sensitive	

Specific functions with each functional group are identified in Table 3-3. The light weight construction type includes pre-engineered metal skin, wood frame, or similar light weight buildings.

Inclusionary siting guidance is presented graphically in Fig. 3-1 and in matrix form in Table 3-4. In Fig. 3-1, functional groups are represented by an appropriate symbolic icon and the associated construction type is depicted by the shading pattern of each icon. Figure 3-1 should be interpreted as allowable function and construction type within each zone. For example, within Zone 3 (500 to 1000 ft from the hush house) recommended uses are aircraft maintenance and industrial for single story masonry construction

Table 3.3. Functional hush house and airfield land uses.

Group	Common Functions	Category Codes
1 - Aircraft Operations and Maintenance	test cell	211-183
	hush house	211-189
	general purpose	211-152
	jet engine shop	211-157
	corrosion control	211-159
2 - Industrial	warehouse	422-758
	petroleum operations	121-111
	hydrant fueling	121-122
	POL operation storage	124-135
3 - Administrative	wing/group HQ	610-244
	CBPO	610-119
	Civilian personnel	610-128
	family services	740-253
4 - Community	commissary stores	740-266
	exchange sales stores	740-388
	bank/credit union	740-15x
	central post office	730-443
	schools	730-78x
	chapel	730-771
	museum	760-111
	library	740-243
5 - Medical	hospital	510-001
	dental clinic	540-243
6 - Housing	family housing	711-1xx
	TLF	740-457
	BOQ	724-415
	UEPH	721-312
	VOQ	724-417
	VAQ	721-315
7 - Vibration Sensitive	avionics shop	217-712
	PMEL	218-868
	explosives storage	422-25x
	hazardous storage	442-25x

Table 3-4. Matrix of nearest recommended zone for function and construction type.

	Masonry		Light Weight	
	single story	multi-story	single story	multi-story
Group 1 - aircraft operations and maintenance	3	4	4	5
Group 2 - industrial	3	4	4	5
Group 3 - administrative	4	4	4	5
Group 4 - community	4	4	4	5
Group 5 - medical	6	6	6	6
Group 6 - housing	5	5	6	6
Group 7 - vibration sensitive	4	5	5	6

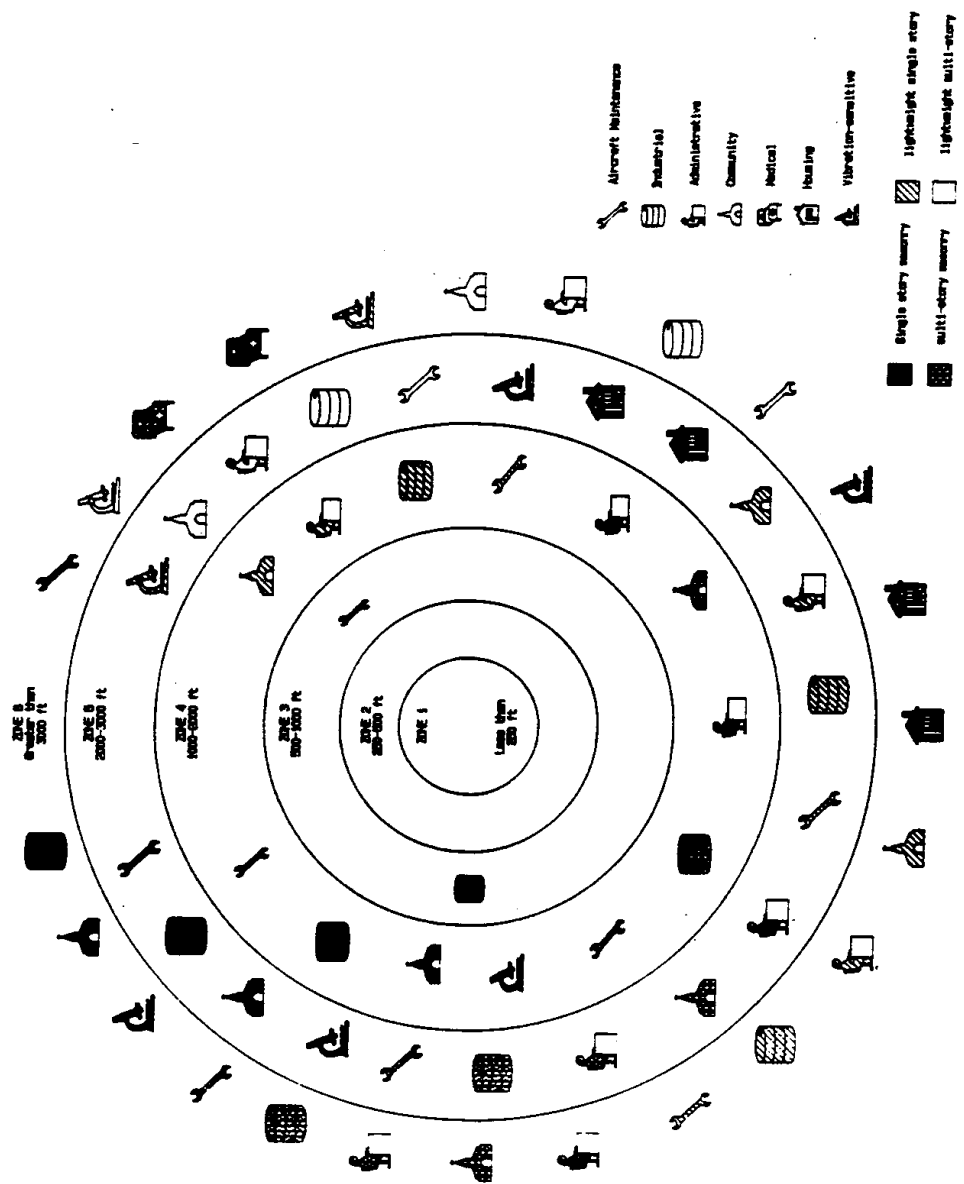


Figure 3-1. Siting guidance based on land use function and construction type.

only. Other combinations of function and construction type are discouraged within this zone. As evident in Fig. 3-1, land uses are less restricted, based on noise and vibration impacts, at greater distances from the hush house (Zone 4, 5, and 6).

Table 3-4 presents information identical to that provided in Fig. 3-1, but in matrix form. Each element in this matrix is the nearest zone recommended for the siting of the indicated function and construction type. For example, the number 3 is the element associated with the aircraft maintenance function in a single story masonry structure. This means that single story masonry buildings used for aircraft maintenance should be sited no closer to a hush house than Zone 3. Thus, siting of such facilities is recommended for Zones 3-6.

(3) Zone 1 (within 250 ft of a hush house) is recommended as an absolute exclusionary zone. Significant structural damage has occurred at one single story masonry building sited within this zone. While this damage can not be absolutely linked to hush house operations, this cause is strongly suspected. No functions are recommended for siting in Zone 2 (250 to 500 ft from a hush house). This is not necessarily an absolute exclusionary region; however, minor structural damage has been reported at one single story masonry facility sited within this zone. No evidence exists to suggest that this damage is hush house induced. Siting facilities in this region is discouraged.

(4) This siting guidance should be used as part of the land use planning process. It is recognized that siting constraints resulting from noise and vibration related impacts may present conflicts with other land use requirements. In such cases, relaxation of the noise and vibration impact based siting guidance may be required. In light of the fact that these

impacts have forced the abandonment of one facility, discretion is advised. The following provides guidance for dealing with conflicts.

(a) Interference with function will likely be intermittent, short duration (20 seconds, or less) and for the most part associated with engine testing in the afterburner mode. Interference with function can be minimized by coordination of schedules for these functions and tests. Engine testing in the afterburner mode could be avoided during periods when critical noise or vibration sensitive functions are to be performed or conversely, sensitive functions should not be performed during the short and infrequent periods when engine testing in the afterburner mode is scheduled.

(b) Structural vibration may be reduced by hardening a vibration sensitive facility. For a new facility, this can be accomplished by designing and constructing a more massive wall on the side of the facility which faces the hush house. This wall should have no door or window openings. In this manner, a building of light weight construction could be sited closer to a hush house by utilizing masonry construction on a single wall. A similar strategy could be employed to remediate vibration problems at existing single story facilities. Here, a single story massive wall could be erected between the hush house and the impacted facility. Walls could be masonry or other heavy material. Double walls of light weight material could be erected and the gap backfilled with sand. Mitigation by hardening requires the use of walls with large mass per unit area. Hardening would offer protection against bomb threats and could be required in the European theatre (USAFE).

3.2.7 Compatible and Incompatible Land Uses or Facilities

Sites selected for the hush house/sound suppressors should not create an incompatible situation for adjacent functions or land uses. Ensure that

adjacent facilities will meet the AFMs 19-10, Figure 4-5, Acceptable Land Uses and Minimum Building Sound Level Requirements.

(1) It should be noted that compatible noise and acceptable noise or vibration may be perceived differently by personnel affected.

(2) A location which affects adjacent functions may be noncompatible based on the perception of high noise or excessive vibration levels. Recommend dense sites or sites with mixed land uses be carefully reviewed to ensure that unwanted noise or vibration does not become a nuisance. Personal judgment may be the best safeguard against problems which defy definition.

3.3 Site Planning and Development

3.3.1 Review of Base Comprehensive Plan (BCP,

Site selection for the hush house should be based on land use compatibility, functional linkage with adjacent facilities and utility support. The hush house function is closely linked to flight line or engine overhaul areas. A strong justification exists for locating off an existing ramp or taxiway. Accessibility to the jet engine overhaul facility or aircraft parking area is of immediate interest.

(1) Review the BCP Tabs to ensure potential areas for development are available for a hush house.

(2) Check distances to the fire department to ensure a quick response in the event of an engine or aircraft fire.

(3) Ensure the site selected provides adequate separation from medical facilities, PMEL, avionics and electronic repair facilities, and housing areas.

(4) Avoid locations near fuel cell docks, POL storage or other potentially volatile liquid operations, and explosive storage areas.

3.3.2 Site Preparation and Development

(1) The sound suppressor site location should be free of development constraints which would create excessive site preparation or utility costs. Ensure that the location is not sited in a located which requires waivers of airfield planning criteria or explosive safety standards.

(a) Ensure that ramp taxiway and runway airfield planning criteria setbacks are maintained.

(b) Waivers to explosive safety siting criteria outlined in AFR 127-100, Explosives Safety Standards, are not usually considered mission essential for the siting of hush houses.

(2) Foundation details are shown on AF Drawing 8045580 and loadings are shown on AF Drawing 8045582. Drawing 8045580 Sheet 1, Note 4A thru L, shows what materials are not supplied by noise suppressor, hush house contractor. Materials not supplied by the contractor are as follows:

(a) Concrete and reinforcement required for foundations and grade slabs.

(b) Electrical service from local utility to site, including conduit stub up and wiring to the hush house location.

(c) Telephone and/or other communication service from local utility to site, including conduit stub up, all wiring and all other required equipment.

(d) Potable water service from local utility to site, including conduit stub up, all wiring and all other required equipment.

(e) Wastewater system including fuel/water separator from site to a designated disposal area. System to receive the contaminated water from the floor drains. Drains must be capable of preventing back flow due to four inch water pressure drop within enclosure.

(f) Heating elements required for cold water sites to prevent frost damage to potable water systems.

(g) Ground system and all associated accessories required for aircraft, test equipment, and ground support equipment.

(h) Lightning protection system and associated accessories.

Requirement for such protection system shall be determined and specified by user activity.

(3) Static and equipment grounds should be provided for each aircraft space, in accordance with AFM 88-15. Recommended six grounding points to accommodate aircraft with aircraft ground support equipment (AGE) and user activity.

(a) One on the approach ramp.

(b) Three in the main test area (one adjacent to equipment room).

(c) Two located adjacent to fuel trailer and start cart pad.

(4) Additional hush house support:

(a) Latrines should be included at the site to support hush house personnel.

(b) Fire hydrants should lie within or be within the required distance of the hush house location.

(c) Fuel support storage facilities should include a containment area/basin.

(d) Water washdown capacity and pressure should be adequate to support jet engine maintenance and wastewater.

VOLUME II:

ANALYSIS OF IMPACTS OF-HUSH HOUSE OPERATIONS

A. Witten
C. Easterly
M. Lessen¹
R. Miller
M. Swihart²

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
Martin Marietta Energy Systems Inc.
for the
U.S. Department of Energy
under contract DE-AC05-840R21400

1. Consulting Engineer
2. University of Tennessee, Knoxville

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SUMMARY

Oak Ridge National Laboratory (ORNL), in support of the U.S. Air Force Logistics Command, has investigated the potential impacts that could occur as a result of the operation of hush houses. Hush houses are hangerlike structures used for the diagnostic testing of aircraft engines. These facilities are designed to acoustically isolate the aircraft engine noise while providing an operating environment which allows proper engine function. This study considers the three types of hush houses which are currently operated by the U.S. Air Force; the T-10 and T-11 which can accommodate fighter aircraft and their engines, and the T-9 which is used for the testing of engines from larger aircraft such as bombers and cargo planes.

This study focuses on the following issues: the physical (functional interference, structural damage) and physiological (annoyance, startle caused by the sudden onset of vibrations) impacts of the low frequency acoustic energy (infrasound) produced by hush house operations and the resulting induced structural vibrations, the impacts of audible noise (interference with conversation) emitted from hush houses, and the changes in air quality which result from hush house air pollutant emissions. The analyses presented here are based on published information, observations by ORNL staff of several operating hush houses, and responses to a telephone survey of installations with operational hush houses conducted by ORNL.

The only impacts identified here which could conflict with land use functions at most installations are those associated with the infrasonic hush house emissions. These impacts include annoyance and startle associated with human exposure to infrasound or the vibrations it induces; as well as interference with vibration-sensitive functions such as avionics and precision measurement equipment laboratories, and structural damage to nearby buildings. The spatial extent of these impacts will depend upon the function and construction type of nearby buildings and can be summarized by means of zones of influence. Each zone is defined by a minimum distance from a hush house beyond which building use functions are not expected to experience significant impacts. Since vibroacoustic impacts will depend on building construction type as well as function within each zone, construction type may be limited for each function. These zones of influence are:

ZONE 1 - MINIMUM DISTANCE FROM HUSH HOUSE = 500 FT

<u>Function</u>	<u>Construction Types</u>
1. workshops and single story offices	masonry with 15-25% door and window openings
2. PMEL, avionics and other vibration-sensitive functions	single story concrete block with no large door or window areas on walls facing the hush house

ZONE 2 - MINIMUM DISTANCE FROM HUSH HOUSE = 1000 FT

<u>Function</u>	<u>Construction Type</u>
1. offices, workshops, community, and other non-vibration-sensitive functions	multi-story masonry with 15-25% door and window areas, single story pre-engineered steel

ZONE 3 - MINIMUM DISTANCE FROM HUSH HOUSE = 2000 FT

<u>Function</u>	<u>Construction Type</u>
1. housing	unrestricted
2. non-vibration-sensitive work-related functions	unrestricted
3. vibration-sensitive functions	multi-story masonry, single story pre-engineered steel

ZONE 4 - MINIMUM DISTANCE FROM HUSH HOUSE = 3000 FT

<u>Function</u>	<u>Construction Type</u>
1. medical	unrestricted
2. vibration-sensitive functions	unrestricted

The low frequency components of the audible spectrum produced by an operating hush house are of sufficient magnitude to cause loss of hearing under conditions of prolonged exposure. However, significant sound pressure levels have only been observed during operations in afterburner mode. Since afterburner operations are infrequent and short-term (20 seconds or less),

impacts of audible noise are not significant beyond 250 ft from the hush house.

Because atmospheric pollutant emissions from hush houses are sufficiently low, air quality is only an issue at facilities in which ambient air quality is quite poor. Potential for air quality impacts depend upon ambient air quality, local meteorological conditions and distance to the site boundary or base housing (the points at which air quality standards are applied).

This study serves to identify more focused future studies and can be the basis for the development of quantitative and comprehensive siting criteria as more information becomes available. The study concludes that the implementation of mitigation measures applied at the source (the hush house) would likely be less restrictive and be a more cost effective mitigation measure than a strategy that exclusively relies on siting restrictions.

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1. DESCRIPTION OF THE STUDY

1.1 Background

Hush houses are hanger-like structures designed to isolate the aircraft engine noise associated with diagnostic engine tests from the surrounding environment. Two types of hush houses are operational in the United States: the T-10 and the T-9. The T-10 hush house (Fig. 1.1) is used for jet fighter engines and can accommodate either a bare engine mounted on a stand or installed in the aircraft. Figures 1.2a and b are horizontal and vertical cross-sectional perspectives of the T-10 hush house. Figure 1.3 illustrates the configuration for bare-engine operation. The sidewalls of the structure are composed of acoustic baffles designed to allow airflow into the building and attenuate sound leaving the building. Air enters the interior of the building through five air inlet doors on each interior sidewall. Air entering through the four doors forward of the control and equipment rooms is drawn into the engine air inlet. Air passing through the six rear sidewall inlet doors is entrained by the flow of engine exhaust gas as it enters the augmentor tube (identified as the Air Cooled Muffler in Fig. 1.2a). This air can mix with the exhaust gas to reduce its temperature as it moves through

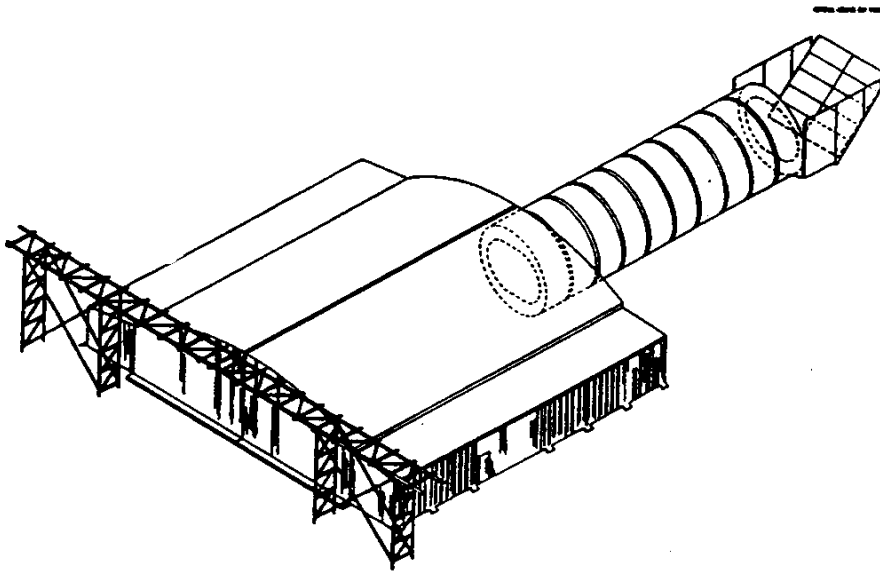
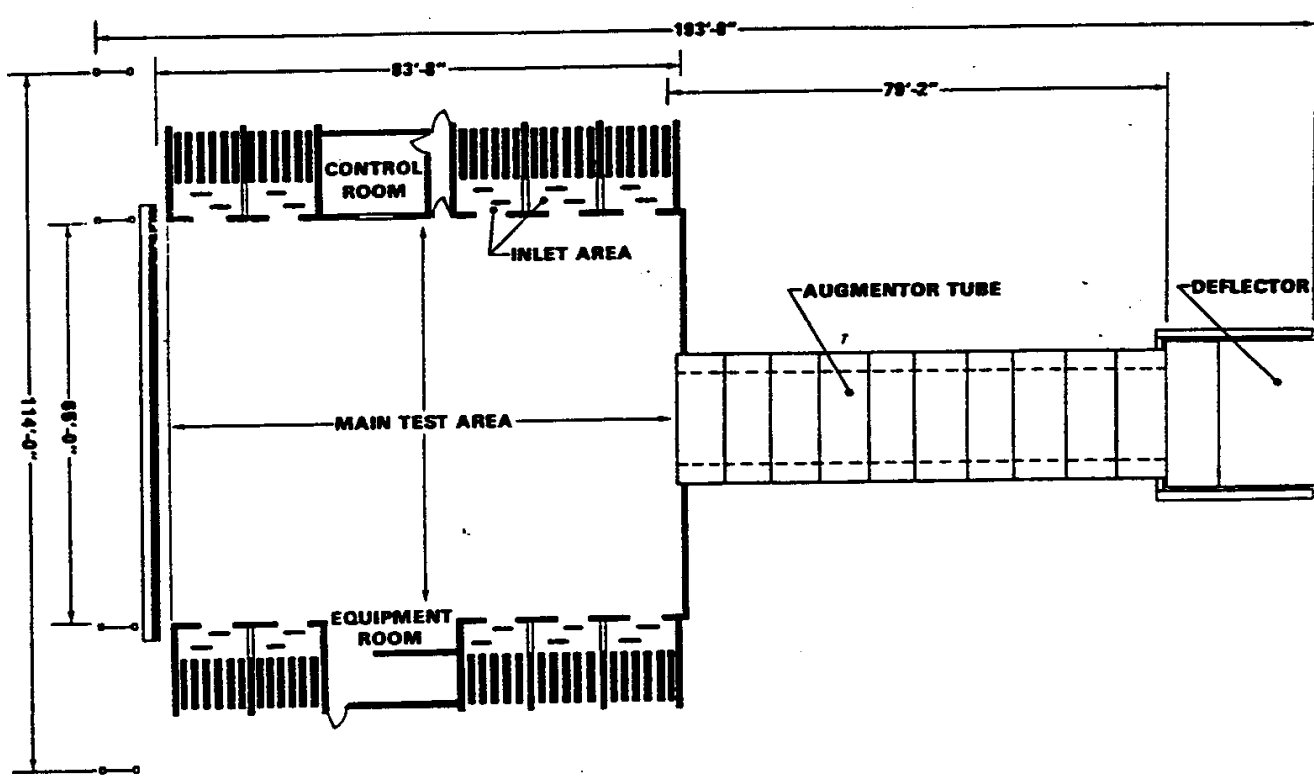
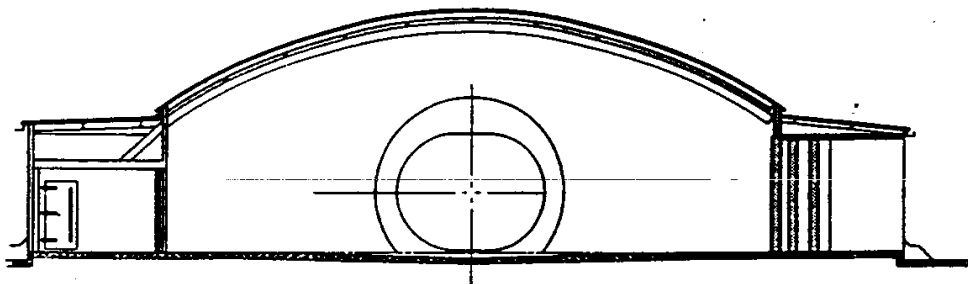


Figure 1.1 Sketch of a T10 hush house.



(a)



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Figure 1.2 Sketch of a hush house as viewed from (a) above and (b) the front.

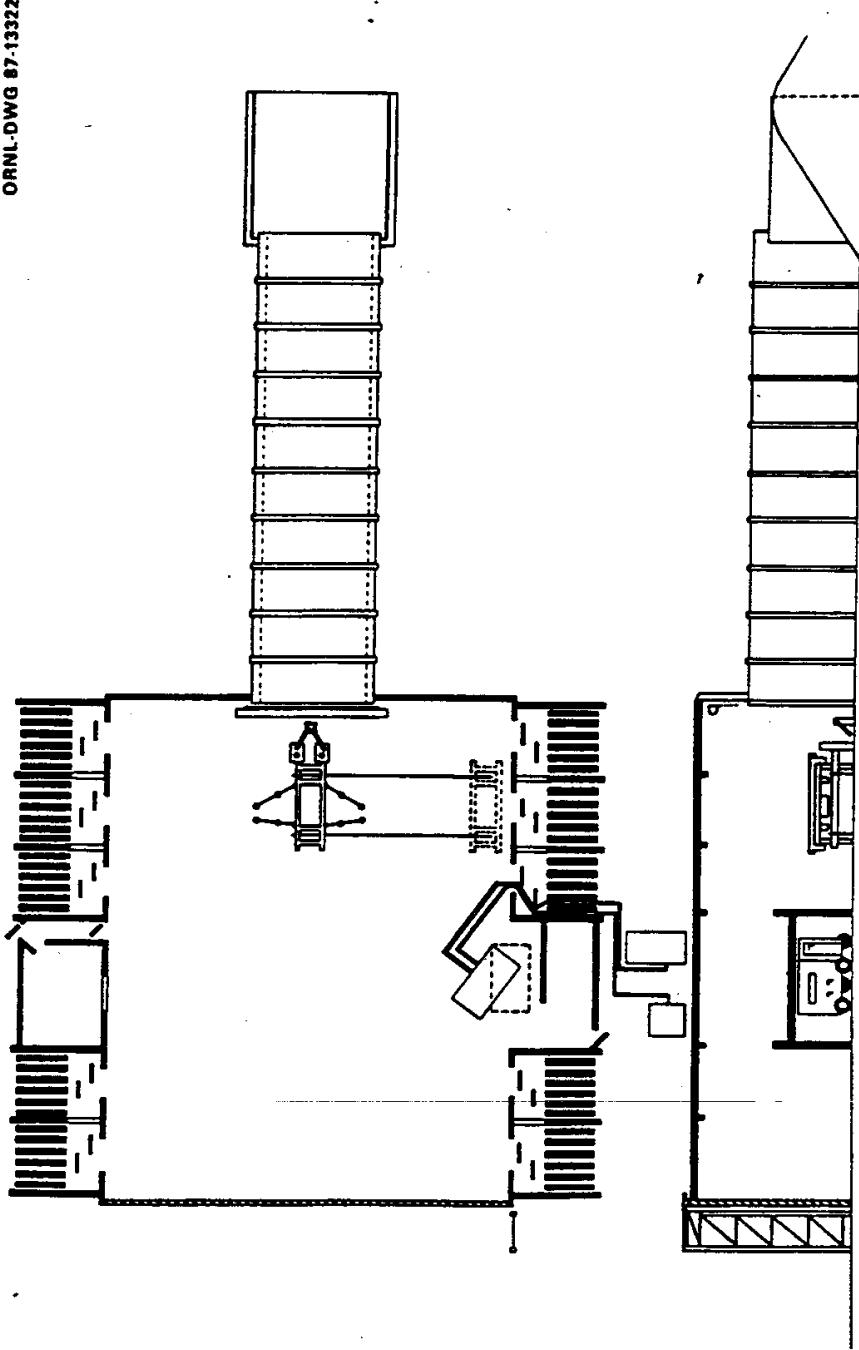


Figure 1.3. Sketch of engine stand configuration or bare engine testing.

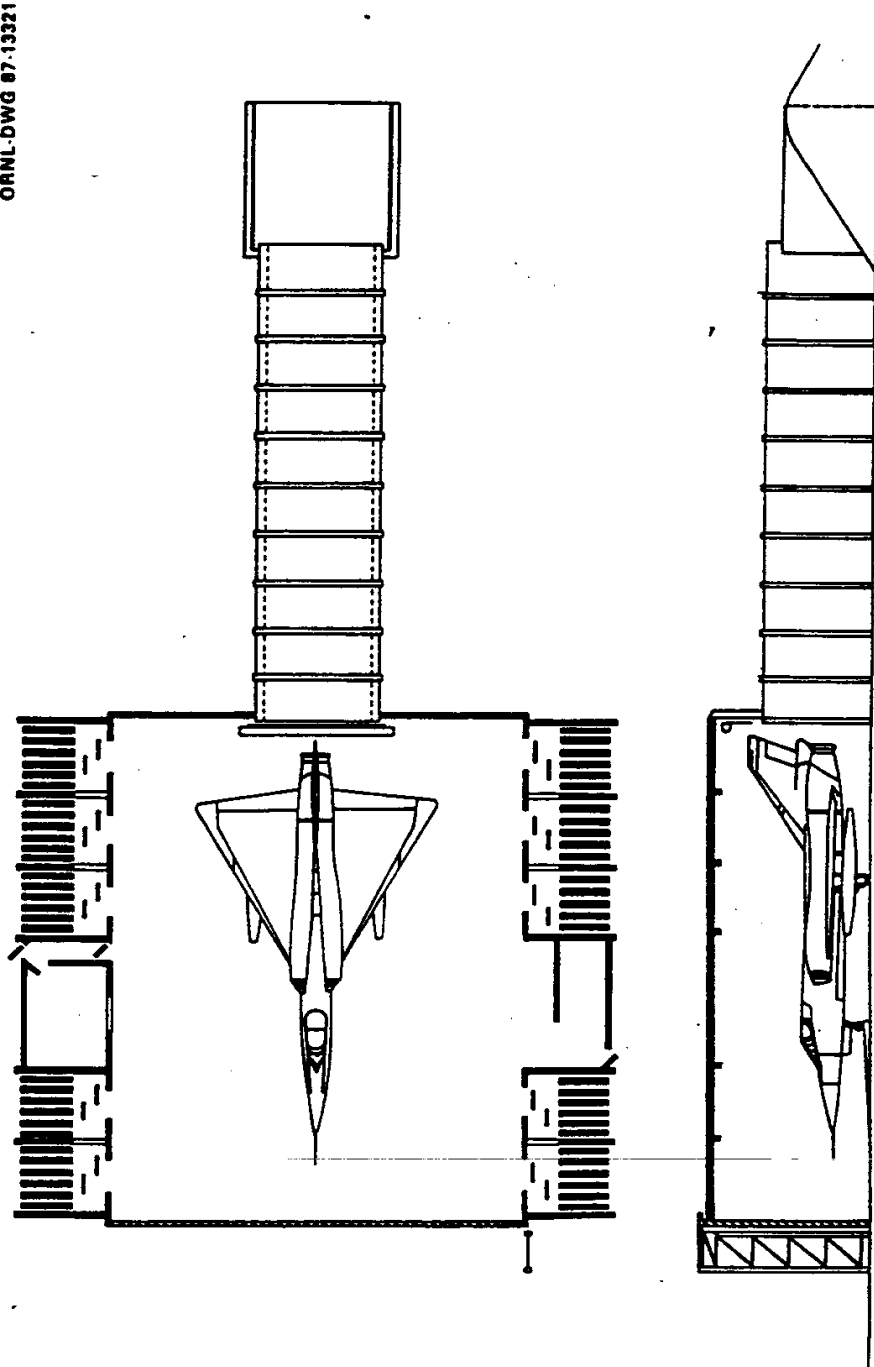


Figure 1.4. Sketch of configuration used for the testing of an engine installed in an F-106 aircraft.

the augmentor tube. The augmentor tube is the conduit through which exhaust gas exits the hush house. It is 79 ft long, oval in cross-section, and terminates at a 45° ramp deflector which imparts a vertical component to exhaust flow (Fig. 1.3). The front doors of the hush house are filled with sound absorbing material. Figure 1.4 shows the position of the F-106 in the hush house. In order to minimize both thermal stress on the walls of the augmentor tube and engine backpressure, it is important to achieve close alignment of the axes of the engine and augmentor.

The T-9 hush house (Fig. 1.5) is designed to accommodate engines from larger aircraft such as the KC-135, B-1, etc. These facilities are designed for the operation of bare engines only, with the engine suspended from above in a manner similar to its mounting below a wing (Fig. 1.6). The sidewalls of the T-9 hush house are solid. Air enters the building through open acoustic baffles above the front doors and through the rear wall beside the front of the augmentor tube. Air entering through the front is drawn into the engine while air entering through the rear is entrained by the engine exhaust flow in the augmentor tube. The T9 augmentor tube is identical to

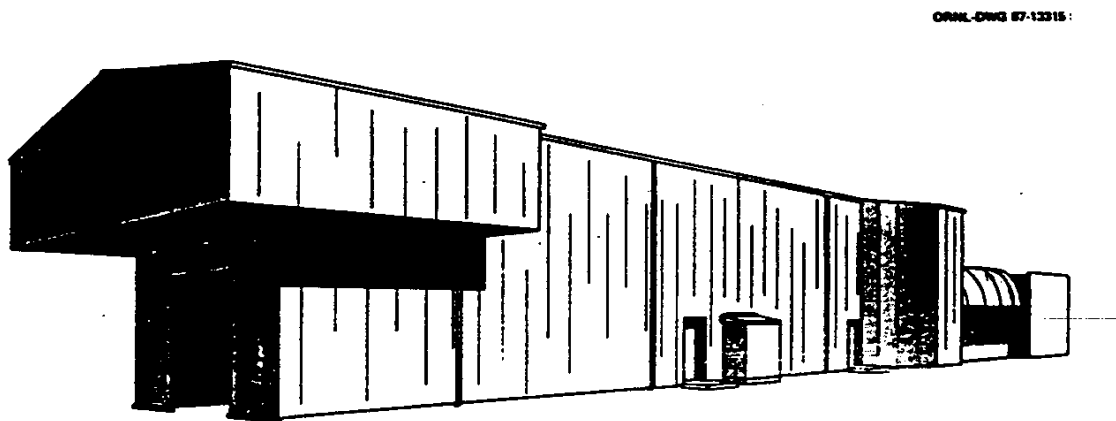


Figure 1.5. Sketch of a T9 hush house.

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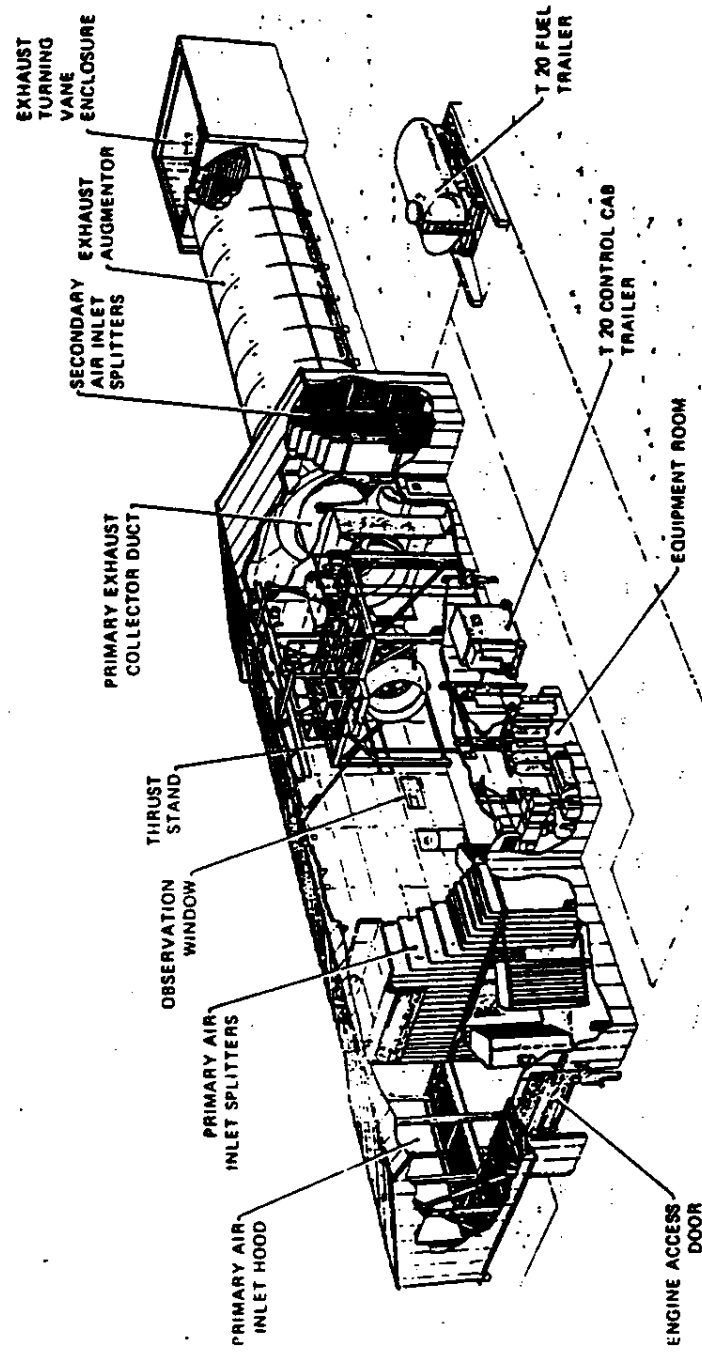


Figure 1.6. Sketch of a T-9 hush house showing an engine suspended from thrust stand.

that for the T-10 but terminates at a steeper deflector made up of an array of turning vanes.

A third type of hush house, the T-11, is used for operations in Europe. The T-11 is identical to the T-10 except that the T-11 is wired for European current.

There are approximately 50 operational T-10 hush houses. The earliest began service in 1981. There are currently only two operational T-9 hush houses. The original T-9 which has been in service about one year is located at McConnell AFB and is used by SAC. The second is at Sky Harbor International Airport, in Arizona, and is used by the Air Guard. This unit was completed several months ago. Several T-9 hush houses are currently under construction and more are planned. Table 1.1 shows the schedule for initial operations for all of the Air Force's hush houses (T-9, T-10, and T-II) worldwide.

1.2 Scope

The primary motivation behind the development of the hush house was noise suppression. Prior to the initiation of hush house operations, open air engine tests produced significant noise impacts both within and beyond base boundaries. Following the construction of a hush house, the facility must undergo a series of acceptance tests (U.S. Air Force, 1983) to ensure that it complies with design specifications. The only environmental parameter included in these tests is noise. Noise measurements are made on two semi circular arcs each having a radius of 250 ft (Fig. 1.7); one centered at the front and the other the rear of the augmentor tube. Ten measurement locations are distributed over 18. intervals on each arc. Because the hush house is symmetric about its axis, measurements are not required at all ZO points. Instead, measurements can be at the 10 points either to the left or right of the axis (points 1-10 or 11-20 in Fig. 1.7, respectively). To meet Air Force criteria, the A-weighted sound pressure levels must not exceed 89 dB at any of the measurement locations. Because of the obvious noise concern and because the hush house produces sound pressure levels at the lower range of the audible spectrum far in excess of 89 dB, noise is an important element of this study.

A related issue addressed here is subaudible, low-frequency, pressure waves (infrasound). These hush house emissions have produced substantial

Table 1.1. Location, command, and initial operations date for USAF hush house projects (schedule current as of 5/84; no current schedule available: personal communications with SAALC/MMIMH).

Base	Command	Location	Initial Unit No.	Operation
Alconbury	AFE	RAF England	1	01/86
Alconbury	AFE	RAF England	2	10/87
Andrews	ANG	Washington, DC	1	10/81
Ankara	AFE	Anakara AS Turkey	1	09/90
Ankara	AFE	Anakara AS Turkey	2	12/90
Atlantic City	NGB	Atlantic City Apt. NJ	1	04/90
Bergstrom	AFR/TAC	Austin, TX	1	03/85
Bergstrom	ARF/TAC	Austin, TX	2	11/88
Birmingham	ANG	Birmingham, AL	1	07/87
Bitburg	AFE	Bitburg W 6ermany	1	09/82
Bitburg	AFE	Bitburg W. Germany	2	06/84
Boise	ANG	Boise, ID	1	10/87
Buckley	NGB	Denver, CO	1	01/90
Burlington	ANG	Burlington, VT	1	06/83
Byrd/AP	ANG	Richmond, VA	1	10/88
Cannon	TAC	Clovis, NM	2	08/89
Cannon	TAC	Clovis, NM	1	08/83
Cannon IAP	AN6	Reno, NV	1	09/89
Capital Aprt	NGB	Springfield, IL	1	11/83
Carswell	AFR	Ft. Worth, TX	1	07/84
Clark	PAF	Manila, Luzon	1	08/86
Clark	PAF	Manila, Luzon	2	08/86
Camp New Amsterdam	AFE	Wetherlands	1	07/83
Danneley Field	ANG	Montgomery, AL	1	04/89
Des Moines	NGB	Panama City, FL	1	07/86
Dobbins	ANG	Marietta, GA	1	12/82
Duluth	AN6	Duluth, MN	1	09/88
Edwards	SYS	Lancaster, CA	1	04/85
Eglin	SYS	Ft. Walton, FL	1	11/83
Eglin	TAC	Ft. Walton Beach, FL	2	11/87
Eglin	TAC	Ft. Walton Beach, FL	3 .	11/87
Ellington	N6B	Houston, TX	1	01/87
Elmendorf	M C	Anchorage, AK	1	08/82
Fresno	AN6	Fresno, CA	1	03/89
Ft. Smith	AN6	Ft. Smith, AR	1	08/82
Ft. Wayne	AN6	Ft. Wayne, IN	1	11/82
George	TAC	Victorville, CA	2	11/86
George	TAC/TAC	Victorville,CA	1	11/86
Great Falls	AN6	6reat Falls, MT	1	07/88
Greater Pitt	N6B	Pittsburgh, PA	1	12/86
Griffiss	ADAC	Rome, NY	1	09/83
Hahn	AFE	Hahn AB, W. 6ermany	1	11/82
Hahn	AFE	Hahn AB, W. 6ermany	2	07/84
Hector Field	AN6	Fango, ND	1	07/84
Hickam	N6B	Honolulu, HA	1	06/90

Table 1.1. (Continued)

Base	Command	Location	Initial Unit No.	Operation
Hill	TAC	Ogden, UT	1	06/85
Hill	ARF/TAC	Ogden, UT	2	12/88
Hill	TAC	Ogden, UT	3	02/90
Holloman	TAC	Alamogordo, NM	1	05/89
Holloman	TAC	Alamogordo, NM	2	10/89
Homestead	TAC	Homestead, FL	1	02/88
Homestead	TAC	Homestead, FL	2	12/89
Hullman Field	ANG	Terre Haute, IN	1	04/83
Jacksonville	ANG	Jacksonville, FL	1	02/81
Joe Foss Field	NGB	Sioux Falls, SD	1	12/84
Kadena	PAF	Kadena A8, Okinawa	1	05/83
Kadena	PAF	Kadena AB, a	2	09/87
Kadena	PAF	Kadena A8, Okinawa	3	05/88
Keflavik	EDTAC	Keflavik NS, Iceland	1	08/88
Kelly	ANG	San Antonio, TX	1	05/81
Key Fld	NGB	Meridian, MS	1	05/90
Kfrtland	NGB	Albuquerque, NM	1	03/90
Kunsan	PAF	Kunsan AB, Korea	1	12/82
Kunsan	PAF	Kunsan AB, Korea	2	03/84
K. 1. Sawyer	ADAC	Marquette, MI	1	12/82
Lakenheath	AFE	RAF, UK	1	08/82
Lakenheath	AFE	RAF, UK	2	06/84
Lambert	ANG	St. Louis, MO	1	12/81
Langley	ADTAC	Hampton, VA	1	02/85
Langley	TAC	Hampton, VA	2	03/87
Lincoln	ANG	Lincoln, NB	1	01/89
Luke	TAC	Glendale, AZ	1	04/83
Luke	AFR/TAC	Glendale, AZ	2	12/85
MacDill	TAC	Tampa, FL	1	08/84
MacDill	TAC	Tampa, FL	2	01/89
March	ANG	Riverside, CA	1	09/84
McChord	ADTAC	Tacoma, WA	1	08/85
McClellan	AFLC	Sacramento, CA	1	11/84
McClellan	AFLC	Sacramento, CA	1	02/88
McConnell	NGB	Wichita, KS	1	10/84
McConnell	NGB	Wichita, KS		
McEntire	ANG	Columbia, SC		
McGuire	NGB	Trenton, NJ1		11/85
Minot	ADAC	Minot, ND	1	09/83
Moody	AFLC	Valdosta, GA	1	05/85
Moody	TAC	Valdosta, GA	2	02/87
Mt. Home	TAC	Boise, ID	1	09/86
Mt. Home	TAC	Boise, ID	3	04/88
Nellis	TAC	Las Vegas, NV	1	03/84
Nellis	TAC	Las Vegas, NV	2	03/86
New Orleans	ANG	N.O. Nav Air St., LA	1	08/87

Table 1.1. (Continued)

Base	Command	Location	Initial Unit No.	Operation
Niagara Falls	NGB	Niagara Falls, NY	1	09/84
Niagara Falls	NGB	Niagara Falls, NY	1	09/85
Osan	PAF	.Osan AB, Korea	1	10/85
Otis	NGB	Falmouth, MA	1	07/85
Plattsburgh				04/87
Portland	ANG	Portland, OR	1	02/85
Ramstein	AFE	Ramstein AB, W. Germany	1	02/85
Ramstein	AFE	Ramstein AB, W. Germany	1	10/84
Rickenbacker	ANG	Columbus, OH	1	12/89
Robins	AFLC	Macon, GA	1	06/88
San Juan	ANG	Puerto Rico	1	06/87
Selfridge	NGB	Mt. Clemens, MI	1	03/84
Seymour	TAC	Raleigh, NC	1	12/87
Seymour	TAC	Raleigh, NC	2	11/89
Shaw	TAC	Sumpter, SC	1	05/83
Shaw	TAC	Columbia, SC	2	05/84
Sky Harbor/AP		Phoenix, AZ		
Sioux City				
Municipal Airport	ANG	Sioux City, IA	1	4/87
Spangdahlem	AFE	Spangdahlem AB, W. Germany	1	11/82
Spangdahlem	AFE	Spangdahlem AB, W. Germany	2	10/85
Springfield-Beckley	NGB	Springfield, OH	1	10/86
Standiford	ANG	Louisville, KY	1	05/87
Toledo Exp	NGB	Swanton, OH	1	01/85
Torrejon	AFE	Torrejon, Spain	2	03/85
Tulsa	NGB	Tulsa, OK	1	08/86
Tuscon	ANG	Tuxcon, AZ	1	11/83
Tyndall	ADTAC	Panama City, FL	1	02/86
Upper Hayford	AFE	RAF Upper Hayford, UK	1	01/83
Upper Hayford	AFE	RAF Upper Hayford, UK	2	08/84
WPAFB	AFR	Dayton, OH	1	07/84
Zaragoza	AFE	Zaragonza AB, Spain	1	03/85
Zweibrucken	AFE	Zweibrucken AB, W. Germany	1	12/84
Zweibrucken	AFE	Zweibrucken AB, W. Germany	2	12/85

From: Hush House Schedules, "Talking Paper on Sound Suppressor Schedules,~ Siting and Programming, 5/23/84

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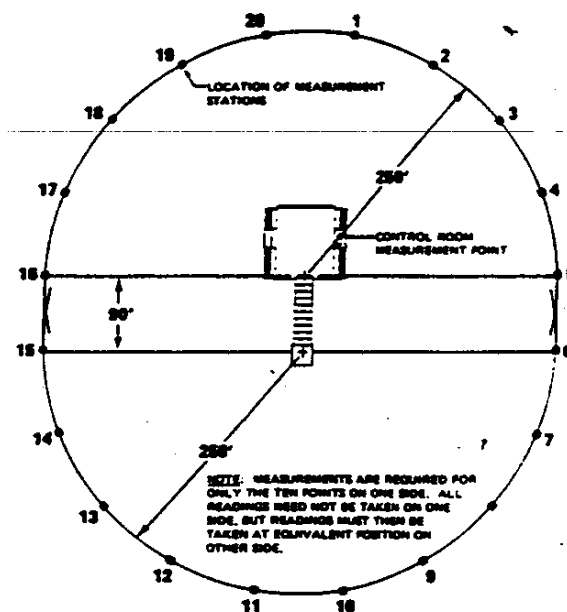


Figure 1.7. Acceptance test noise measurement contour.

vibrations in on-site buildings near some hush houses. The earliest documented impact occurred at Luke AFB (Ver and Anderson, 1984; Battis, 1985). At the present time, only a small number of hush house installations are experiencing this problem. This does not imply that other facilities will remain problem free, but more likely that the engines currently used produce minimal infrasound or that the areas surrounding these hush houses are free of vibration-sensitive buildings or activities. Mission realignments, particularly the conversion to more modern aircraft with different engines, could alter the source (sound) configuration, and necessitate the construction of vibration-sensitive support facilities, such as avionics laboratories. Consequently, it will be useful to understand the zone of influence within which hush operations could interfere with vibration sensitive functions.

The final disciplinary issue addressed in this study is air quality. The concern here is that an engine operating in a hush house may be subject to the regulatory requirements of a stationary source. The precedent for this position has been established in a ruling in California in which the court found that hush houses should be treated as stationary sources (State of California vs. Dept. of Navy, 1980).

The present study will examine hush house-related issues from a perspective of siting and mitigation. The reason for this is that the Air Force is committed to hush houses as a means to minimize noise impacts associated with aircraft engine diagnostic tests. This fact is evident from the hush house operations schedule (Table 1.1). Impacts are evaluated on the basis of zones of influence which, when compared with existing or planned land use patterns in the area surrounding the hush house, yield guidance for siting either new hush houses or new facilities in the vicinity of an existing hush house. For example, noise impacts will be function specific. Noisy environments, such as machine shops, can tolerate greater hush house induced noise levels than functions such as offices. The approach taken here is to define zones surrounding the hush house in which specific functions should be excluded on the basis of noise impacts. While noise and air quality impacts are function specific, the impacts of hush house induced vibrations depend upon the function of a facility, its construction type, and its orientation relative to the hush house. Impacts associated with vibrations include potential health effects, structural damage and disruption of function. Mitigation measures may be applied either at the source (the hush house) or the receptor (the impacted facility). Potential mitigation strategies identified in this study are addressed within the context of zones of influence. In other words, the extent to which a possible mitigation measure serves to reduce the exclusionary zones of influence relative to a particular issue.

The development of comprehensive siting constraints is beyond the scope of this study. This is due to the fact that hush houses operate over a broad range of source/receptor configurations. Each hush house can accommodate many aircraft/engine combinations, each with a unique source (noise, air pollutant concentrations, etc.) characterization, and each Air Force Base has unique land use patterns and constraints which may change with time such as through mission realignment. While the development of quantitative siting criteria can be accomplished with the availability of more extensive field studies, this study is constrained to utilize the limited data that is currently available. This report offers an integrated assessment of impacts which can be used for qualitative siting guidance, serves to identify more focused future studies, and can be the basis for more quantitative and comprehensive siting criteria when additional information becomes available.

2. HUSH HOUSE BASELINE INFORMATION

2.1 Noise and Vibration

2.1.1 Noise

A primary function of the hush house is to provide acoustic isolation of a jet aircraft engine from the surrounding environment. In the case of bare engine test stands the prolonged engine operation associated with normal maintenance procedures produces noise of sufficient magnitude and duration to give rise to health concerns, particularly hearing loss (Baughn, 1973; Burns and Robinson, 1970) and interfere with specific functions in the vicinity of the engine. Thus, the hush house is intended to serve as a means to allow this function to be performed without the necessity for severely restricted land uses within a specified exclusion radius.

The Air Force expects to have about 130 hush houses in operation. All available information from existing hush houses supports the fact that these facilities fulfill the required noise abatement function.¹ This is shown in Table 2.1 which compares maximum A-weighted sound pressure levels, at military power and afterburner, for aircraft installed in a hush house and for open-air ground runup. As evident in this table, the hush house reduces the A-weighted sound pressure levels by more than 50 dB. On site visits to hush houses, ORNL staff members found that engine operations within a hush house did not significantly interfere with normal conversation immediately outside of the hush house. In contrast, the open-air testing of engines from F-106 aircraft at Otis Air Force Base on the Massachusetts Military Reservation routinely resulted in complaints from residents of the town of Mashpee approximately three miles away.

Upon the commencement of operation, each hush house must undergo acceptance tests to establish that the facility meets the criteria set forth in the design. The acceptance criteria with respect to noise abatement is that the A-weighted noise level not exceed 89 dB at any of the twenty or more specified measurement points on the near-circular, 250 ft radius contour shown in Fig. 1.7. Every T-10 hush house currently in operation has met this acceptance criteria. At McConnell AFB, the site of the first T-9, eight different engines were tested. The acceptance criteria employed for these

¹ The limited experience at the only two operational T-9 hush houses suggests that these facilities are not as effective at noise abatement as the T-10.

Table 2.1. Noise levels (dBA) at 250 ft for unsuppressed engine runup (open air), the same engine operating in a hush house (installed) and the difference between the two (insertion loss).

<u>Aircraft</u>	Open Air		Installed		Insertion Loss	
	<u>MP¹</u>	<u>AB²</u>	<u>MP¹</u>	<u>AB²</u>	<u>MP¹</u>	<u>AB²</u>
F-4	123.5	130.6	70.1	79.0	53.4	51.6
F-15			73.9	79.8		
F-16	122.0	129.3	68.7	73.1	53.3	56.2
F-105			70.0	76.7		
F-106			68.2	76.3		
F-111F			68.9	79.6		
T-38			77.6	78.5		
B-1			--	88.7		

¹ Military power

² Afterburner

- Data unavailable

tests was 77 dBA at a distance of 328 ft (100 n). Four of the eight engines tested at McConnell exceeded the noise acceptance criteria with A-weighted noise levels reaching 92 dB at a distance of 328 ft for the F101 (B-IJ engine in afterburner power. The F101 engine was the only engine tested at Sky Harbor International Airport. This engine again exceeded the noise criteria. The maximum noise level recorded at a distance of 328 ft was 88.7 dBA in afterburner mode. Although hush houses satisfy the noise level acceptance criteria, the potential for adverse noise impacts exists as a result of exposure to low frequency, large amplitude sound. Figure 2.1 is a typical sound spectrum 250 ft from the center of the hush house. As can be seen in this figure, the sound pressure levels (SPL) at the low frequencies are quite large ranging from 90 dB at 55 Hz up to about 105 dB at 25 Hz. The SPL decreases markedly with increasing frequency. This reflects both the spectrum of the engine noise and the fact that the performance of acoustic panels improves with increasing frequency. The efficacy of noise abatement panels is directly proportional to the ratio of the thickness of the panel to the wavelength of

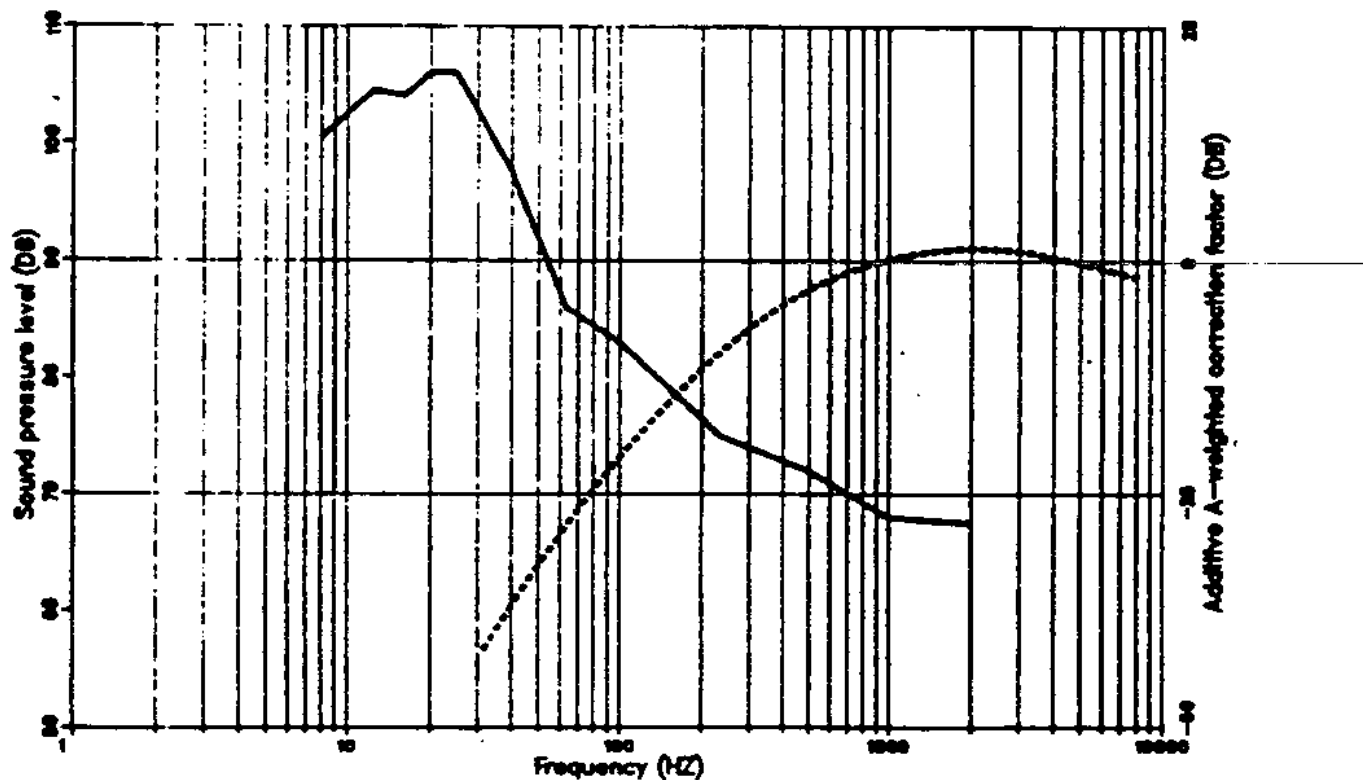


Figure 2.1. Frequency spectrum of F15 aircraft with afterburner operation (solid line) and additive A-weighted correction factors (dashed line). [Data Source: R. A. Lee, personal communications]

the sound. Sound absorbing material that is one or more wavelengths thick can provide excellent noise abatement. For example the wavelength of sound at 10,000 Hz is approximately 1 inch which is quite small with respect to the thickness of the acoustic panels. Acoustic panels that are thin compared to the wavelength generally offer poor noise attenuation. The wavelength of sound at 50 Hz is approximately 20 ft which is greater than the thickness of a hush house's acoustic panel. Thus, the sound suppression characteristics of a hush house are frequency dependent, with noise suppression performance increasing with frequency as depicted in Fig. 2.1.'

Hush houses meet the noise level acceptance criteria because the criteria is based upon the A-weighted average of audible spectral components. The weight factors that reflect the frequency dependent sensitivity of the human ear and are shown as the dashed line in Fig. 2.1. By comparing these weight factors to the actual noise spectrum, it is clear that the averaging system almost completely ignores the most powerful spectral range while placing the greatest significance on a portion of the noise spectrum that contains little power. Table 2.2 presents measured values of maximum sound pressure levels at a distance of 250 ft from the center of the T10 hush house for a variety of engines/aircraft at military power and with afterburner operation.

The sound pressure levels emitted from a hush house exhibit a strong angular dependence relative to the axis of the structure. This is illustrated in Fig. 2.2 which is a polar plot of the sound pressure level at 50 Hz as a function of angle for an engine from an F-106 aircraft in afterburner mode. The strong angular dependence produces the multi-lobed radiation pattern exhibited in this figure. The angular variation in the hush house radiation pattern is a complex function of many parameters including frequency, engine power setting, and whether the engine is bare or installed. The influence of these parameters is displayed in Figs. 2.3-2.5 which show sound pressure levels at three frequencies as a function of angular measurement position over a nearly circular measurement contour (similar to the one shown in Fig. 1.7) for three frequencies and three power settings for both a bare F-100 engine and as installed in a F-15 aircraft. The examination of these figures reveals some interesting features. For low frequencies (50 Hz) and higher power settings, there is a large increase in sound pressure level with angle from the front to the rear of the hush house.

Table 2.2. Maximum sound pressure levels in dB at a distance of ZSO ft from a-10 hush house for a variety of aircraft/engines at different power settings and 8 frequencies. The numbers in parenthesis are the minimum measurement angles as defined in Figure 1.8, at which the maximum value occurs. Data Source R. A. Lee (1982).

	50Hz	100Hz	250Hz	500Hz	1000Hz	2000Hz	5000Hz	10000Hz
<u>Aircraft</u>								
F4/MP	76(60)	78(120)	60(120)	62(0)	60(130)	58(130)	51(80)	48(80)
F4/AB	92(150)	87(130)	72(140)	70(150)	68(150)	65(0)	58(150)	54(70)
F15/MP	82(180)	14(120)	71(150)	69(0)	64(10)	62(170)	52(0)	47(10)
F15/AB	96(160)	83(100)	78(140)	72(180)	69(0)	67(0)	55(10)	49(10)
F16/MP	78(130)	69(40)	68(130)	62(10)	59(0)	55(130)	48(130)	44(70)
F16/AB	95(130)	81(130)	73(120)	61(0)	62(110)	58(0)	48(80)	46(120)
F105/MP	88(160)	73(130)	71(140)	61(180)	58(10)	57(130)	48(90)	42(180)
F105/AB	98(140)	82(170)	77(120)	72(20)	65(20)	63(20)	55(80)	54(60)
F106/MP	85(160)	75(110)	70(130)	61(180)	59(10)	56(10)	48(150)	44(18)
F106/AB	101(180)	83(110)	76(120)	69(10)	66(10)	65(10)	53(90)	53(140)
F111F/MP	85(160)	72(110)	70(130)	57(160)	58(160)	59(0)	49(160)	43(180)
F111F/AB	100(160)	90(120)	79~120)	67(130)	69(170)	68(130)	56(170)	52(170)
T38/MP	68(180)	67(140)	65(180)	74(180)	67(180)	61(180)	47(180)	35(180)
T38/AB	76(180)	66(120)	64(180)	75(180)	69(180)	61(180)	47(180)	35(90)
<u>Engine</u>								
TF41-A-1/MP	86(160)	70(0)	64(110)	65(0)	59(60)	62(60)	49(0)	48(0)
TF41-A-1/MMP	88(180)	71(0)	67(140)	70(0)	64(0)	62(10)	52(10)	48(10)
J79-6E-15/MP	84(150)	69(120)	69(130)	58(10)	59(150)	58(120)	52(0)	52(0)
F100-PW-100/MP	88(170)	76(180)	68(0)	71(0)	65(0)	61(130)	57(180)	55(160)
F100-PW-100/AB	103(180)	84(130)	77(140)	73(0)	71(130)	70(130)	59(110)	58(0)
J75-P-19/MP	96(170)	76(170)	70(180)	76(0)	69(180)	67(180)	64(180)	60(180)
J75-P-19/AB	106(170)	89(130)	72(120)	76(0)	69(0)	65(10)	55(110)	53(130)
J75-P-17/MP	90(150)	73(120)	69(130)	60(150)	61(150)	56(100)	53(120)	55(110)
J75-P-17/AB	101(150)	85(130)	73(130)	65(120)	64(130)	66(130)	51(0)	48(140)
TF30-P-100/MP	88(150)	77(150)	69(140)	60(150)	60(150)	56(140)	50(150)	45(150)
TF30-P-100/AB	103(150)	90(150)	76(140)	68(140)	69(140)	65(~20)	57(140)	49(0)

¹Engine power acronyms: MP = military power; MMP = maximum military power; AB = with afterburner operation

²Minimum measurement angle in degrees as measured from the front of the hush house

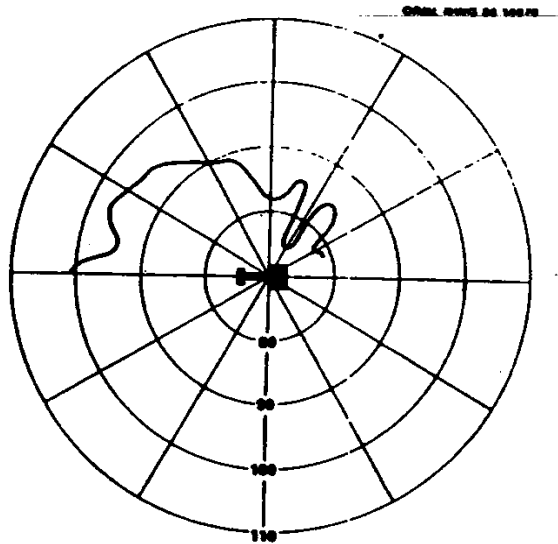


Figure 2.2 Sound pressure level (dB) at 50 Hz as measured at a distance of 328 ft corrected to 250 ft for an F-106 aircraft in afterburner mode in a T-10 hush house. [Data Source: R.A. Lee, 1982.]

This increase is in excess of 20 dB for a bare engine in afterburner mode. For the installed engine the increase in sound pressure level is of a lesser magnitude than for the bare engine. The difference increases with angle varying from 1 dB forward of the hush house to 7 dB at the rear. The angular patterns at the military power level (Fig. 2.3) are quite similar to those for afterburner mode except that all sound pressure levels are reduced by about 15 dB. At 50 Hz and 80% rpm, the angular dependence is less regular and lower in magnitude than for the higher engine powers. At higher frequencies (Figs. 2.4 and 2.5), the situation is quite different. Angular variations in sound pressure levels appear more random in character and do not exhibit any strong dependence on power setting or whether the engine is bare or installed.

The mechanisms by which noise is produced in a hush house is quite complex and impossible to quantify with the data which is currently available. The ultimate driving force behind all acoustic emissions is the operating engine. However, the effect of this operation is manifested as a superposition of many virtual acoustic sources in addition to the direct

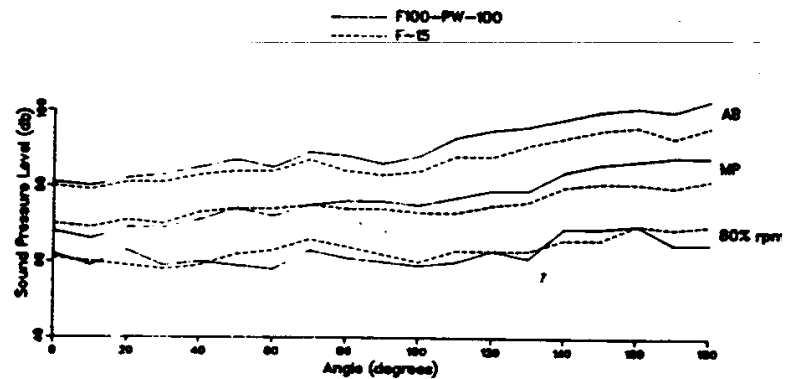


Figure 2.3. Sound pressure levels at a distance of 250 ft from a T10 hush house at 50 Hz as a function of angle on measurement contour for an F100-PW-100 engine bare and installed on an F15 aircraft at 80X maximum RPM, military power, and afterburner. [Data Source: R. A. Lee 1982]

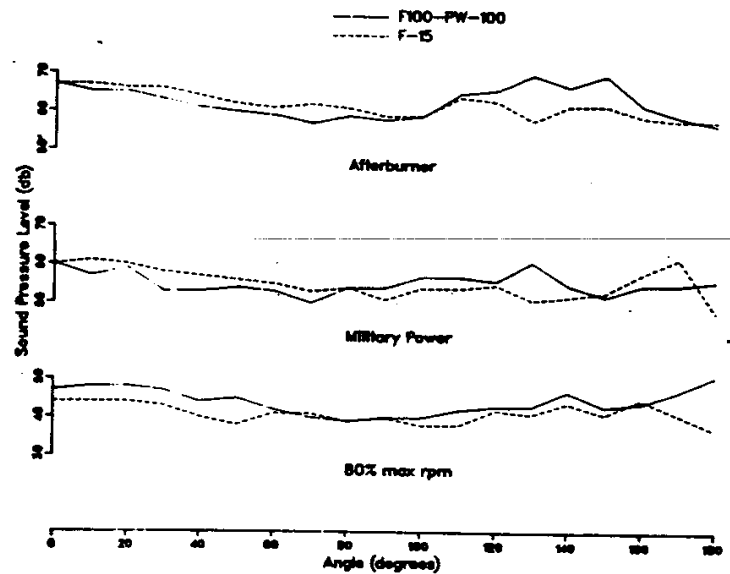


Figure 2.4. Sound pressure levels at a distance of 250 ft from a T-10 hush house and at 2000 Hz as a function of angle on measurement contour for an F100-PW-100 engine bare and installed in an F15 aircraft at 80% maximum RPM, military power, and afterburner. [Data Source: R. A. Lee, 1982]

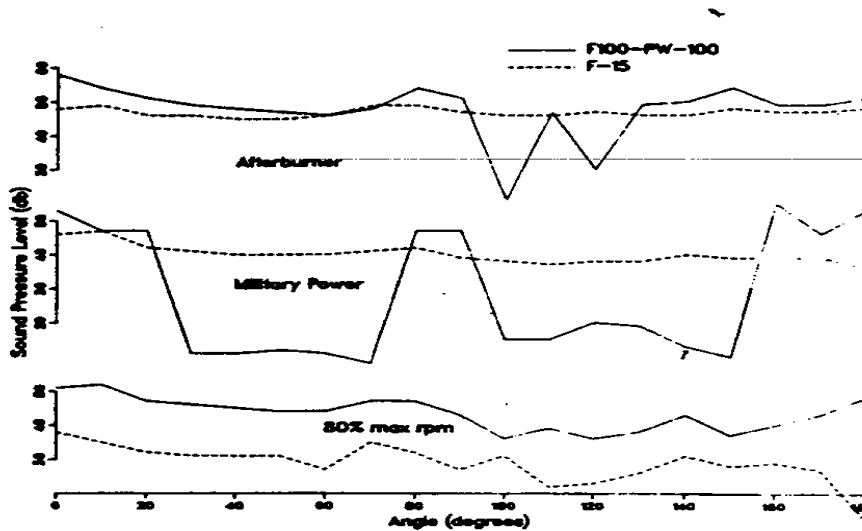


Figure 2.5. Sound pressure levels at a distance of 250 ft from a hush house and at 10,000 Hz as a function of angle on measurement contour for an F100-PW-100 engine bare and installed in an F-15 aircraft at 80% maximum RPM, military power, and afterburner. [Data Source: R. A. Lee, 1982]

engine noise. For example, the hush house intake and exhaust air flow will produce noise possessing different power spectra and source distribution. Intake noise may appear as a distributed source along the hush house side walls while the exhaust noise may be both distributed along the augmentor tube and as a nearly point source at the open end. Additionally, low frequency components of the noise may drive resonant modes of the hush house, augmentor tube, or other smaller structural features of the building (Miller, et al., 1983.).

2.1.2 Infrasound and Vibration

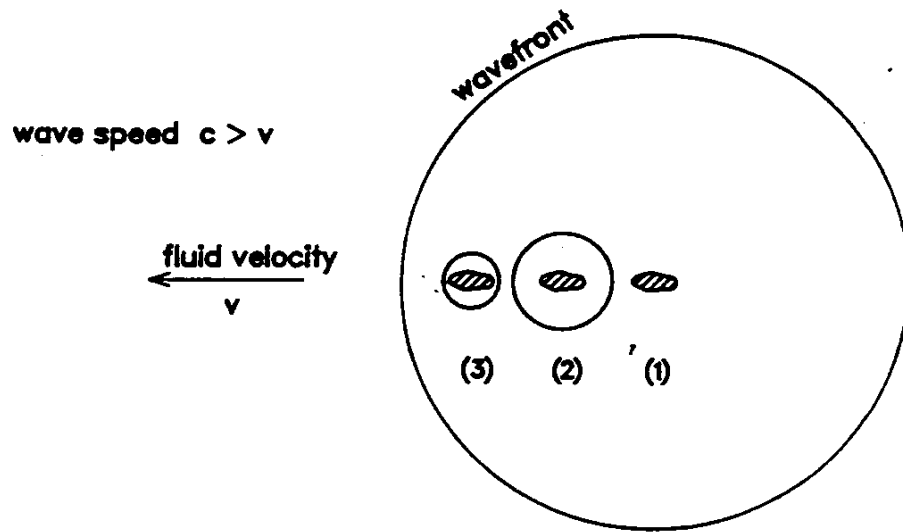
Subaudible (infrasound) emissions from hush houses have induced significant vibrations in neighboring buildings at a number of facilities (Sect. 3.3). The magnitude of this impact ranges from nuisance to concern for structural integrity. At Otis Air Force Base, hush house induced vibrations rattle doors and windows in the crash fire station located to the rear of the hush house and rattle the walls of a parachute drying room in a building beside the hush house. The vibrations induced in the avionics

laboratory adjacent to the Dobbins AFB hush house has necessitated the relocation of this function. Structural damage has occurred at an engine shop adjacent to the Vermont Air Guard hush house at Burlington International Airport. It is presumed that this problem is a result of hush house induced vibrations.

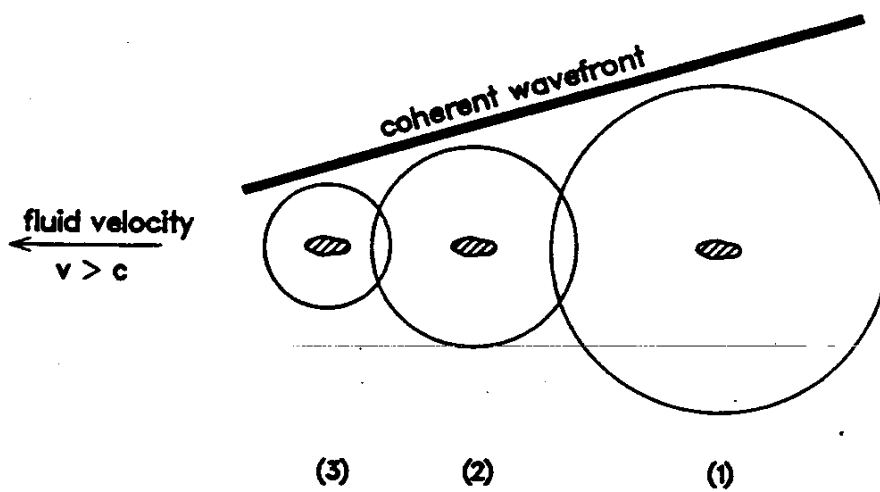
Mitigation of infrasound problems can be accomplished by means of hush house design, siting criteria, nearby land-use constraints, or modified construction practices for buildings to be located near a hush house. However, modification to the hush house design to alleviate vibration problems requires an understanding of the mechanism(s) which is responsible for the infrasonic emissions, a quantification of the source characteristics, and a description of the resulting far-field pressure levels.

The preliminary analysis of vibroacoustic data collected at the Luke AFB hush house (Battis 1985) leads to the important findings that low frequency emissions peak in the 10-15 Hz range and that the infrasonic spectrum resembles that produced by a rocket engine exhaust flow. The Luke experience as well as reconnaissance level information from other facilities indicate that significant low frequency emissions and the associated vibrations occur at the higher engine power settings. It has also been suggested that the low frequency emissions are associated with one, or more, resonant modes of the hush house structure (Miller et al., 1983). These findings suggest that (1) the low frequency emissions are emanating from the high speed portion of the engine exhaust flow as a result of a phenomenon known as acoustic Cherenkov radiation and (2) coupling of this wave energy to the environment external to the hush house occurs through a resonant mode of the augments tube.

Cherenkov radiation can be produced when a gas or stream of charged particles moves faster than a characteristic wave speed in the surrounding medium (Jackson, 1975). Examples of electromagnetic Cherenkov radiation are the blue glow in the water surrounding the core of nuclear reactors and an astrophysical phenomenon known as double radio sources. Acoustic Cherenkov radiation is known to be the cause of low frequency emissions from rocket engines. In this case, the exhaust gas is subsonic with respect to the speed of sound at the elevated gas temperature, but is moving quite fast, faster than the speed of sound in the surrounding air at normal temperature. The mechanism through which acoustic Cherenkov radiation is generated is illustrated in Fig. 2.6. In Fig. 2.6a, a parcel of gas is moving at a



(a)



(b)

Figure 2.6. Illustration of acoustic wave propagating from a parcel of gas moving at a velocity which is (a) less than the speed of sound, and (b) greater than the speed of sound and producing acoustic Cherenkov radiation.

velocity less than the speed of sound in the surrounding region. The wave produced by this gas propagates radially outward. Since the wave is moving faster than the gas, the wave generated at position 1 reaches position 2 prior to the gas parcel which produced this wave. Similarly, a wave created at position 2 precedes the gas arrival at position 3, etc. When the gas velocity is greater than the sound speed (Fig. 2.6b), the gas parcel overtakes the wave which it produced causing successive wavefronts to overlap. This constructive interaction produces a single conical wavefront which is referred to as acoustic Cherenkov radiation. The radiated waveform is similar to a shock cone (Fig. 2.7). A similar situation may occur during jet engine operation. Here, at high power settings, engine exit velocities are about 2000 fps which is faster than the 1100 fps sound speed at standard atmospheric conditions. The temperature of this exhaust gas is almost 2000°F with an associated sound speed of 2400 fps. The existence of acoustic Cherenkov radiation may be inferred from its effect on the structure of the engine exhaust plume. The

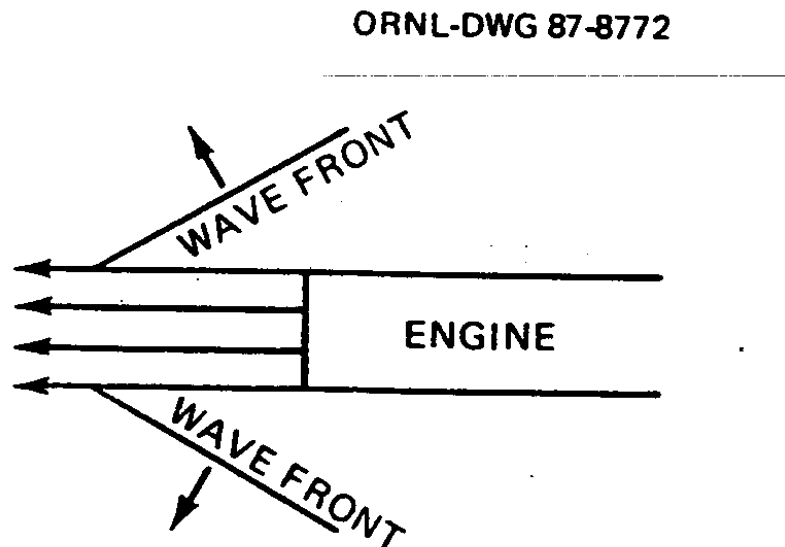


Figure 2.7. Sketch of wavefront produced by acoustic Cherenkov radiation from an aircraft engine exhaust plume.

Jet engine exhaust is a high speed, high Reynolds number flow which, in the absence of acoustic Cherenkov radiation, should be quite turbulent. One effect of turbulence is to cause the plume to spread rapidly so as to reduce both the crosssectionally averaged plume velocity and temperature with downstream distance. This will produce a pattern of isotherms which taper rapidly towards the plume centerline. Spacing between adjacent isotherms will increase with downstream distance. A timeaveraged thermal profile of a turbulent plume is depicted in Fig. 2.8. A second manifestation of turbulence is the transient, dynamic structure it imparts to the isotherms as a result of random eddy motions. This will cause time varying motions which contort the isotherms as illustrated in Fig. 2.9.

The turbulent spreading of a plume results from a hydrodynamic instability in which a small wave created near the plume boundary grows rapidly in amplitude with downstream distance. This promotes mixing which serves to slow and cool the plume. Figure 2.10 is a photograph of this phenomenon in a turbulent plume. It is clear that the rate of spreading of the plume is proportional to the growing wave amplitude. The growth of this wave is inhibited by the presence of acoustic Cherenkov radiation. Energy

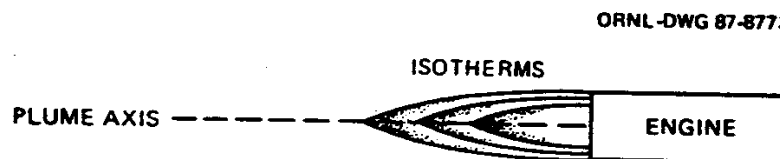


Figure 2.8. Time-averaged thermal structure of a turbulent plume

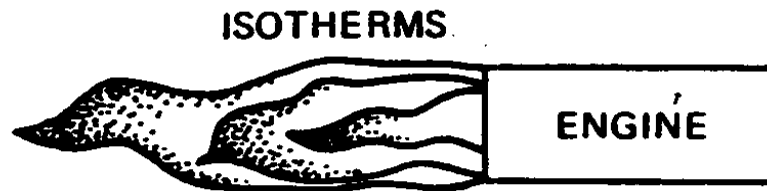


Figure 2.9. Instantaneous thermal structure of a turbulent plume.

removed from the mean exhaust now by the primary wave is, in turn, lost to radiation and, consequently, cannot contribute to the growth in amplitude of this wave. The radiation emitted from each wave crest adds coherently with that from neighboring wave crests to produce a conical wave front (Fig. 2.7). Because of this, the plume can maintain a near constant diameter and temperature for some distance downstream until a point is reached where the instability dominates. Beyond this point, the plume is turbulent. These effects are depicted schematically in Fig. 2.11. Figure 2.12 is a photograph of an F-4 aircraft in a hush house with its engine operating in afterburner mode. Here the gas is sufficiently hot to radiate in the visible spectrum producing the visible flame. Notice that this flame maintains a constant diameter for some distance downstream before it finally tapers and disappears. These features strongly support the suggested presence of acoustic Cherenkov radiation. Further support of this hypothesis comes from estimating the frequency of the Cherenkov radiation. This frequency will be approximately that of the self-excited wave of the primary instability. Applying the linear stability analysis of an



Figure 2.10. Shadowgraph showing growth of the primary instability leading to the spreading of a turbulent plume [Photograph courtesy of Prof. Fritz Bark, Chalmers Institute of Technology, Gothenberg, Sweden]

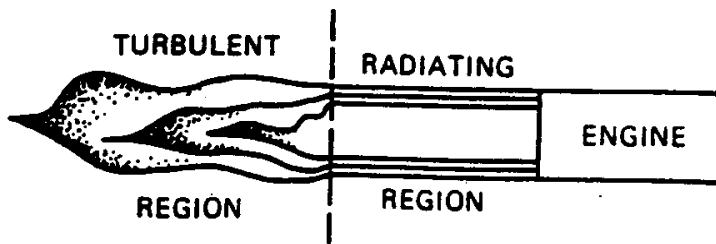


Figure 2.11. Schematic of a high speed engine exhaust flow with a radiating near-field region and a turbulent farfield region.

parameters of a jet engine yields an estimated Cherenkov radiation frequency of 10 Hz. This is consistent with data collected at Luke AFB.

To confirm the existence of acoustic Cherenkov radiation, thermographic images were obtained of the exhaust plume of an F-100 engine in operation in the hush house at Dobbins AFB. Figure 2.13 shows two timelapse sequences obtained from this study. In this figure the thermal structure of the exhaust plume is displayed as gray scale where different shades of gray represent different temperature ranges. Figure 2.13a corresponds to the engine at idle and Fig. 2.13b is at a somewhat higher power setting. Vibration problems have not been reported at nearby facilities for these engine operating levels. Both film sequences display the characteristics typical of a turbulent plume (Fig. 2.9). The isotherms taper continuously from the exit of the engine towards the plume centerline. The effect of eddies is evidenced in both sequences by the transient nature of the thermal structure. The thermal plume is longer in Fig. 2.13b due to the higher power setting and the broad warm area at the downstream end of this figure is from the buildup of heat on the walls of the augmentor tube. Figure 2.14 shows similar thermographic images of time sequences at higher power settings.



Figure 2.12. Photograph of an F-4 aircraft exhaust plume in afterburner mode.

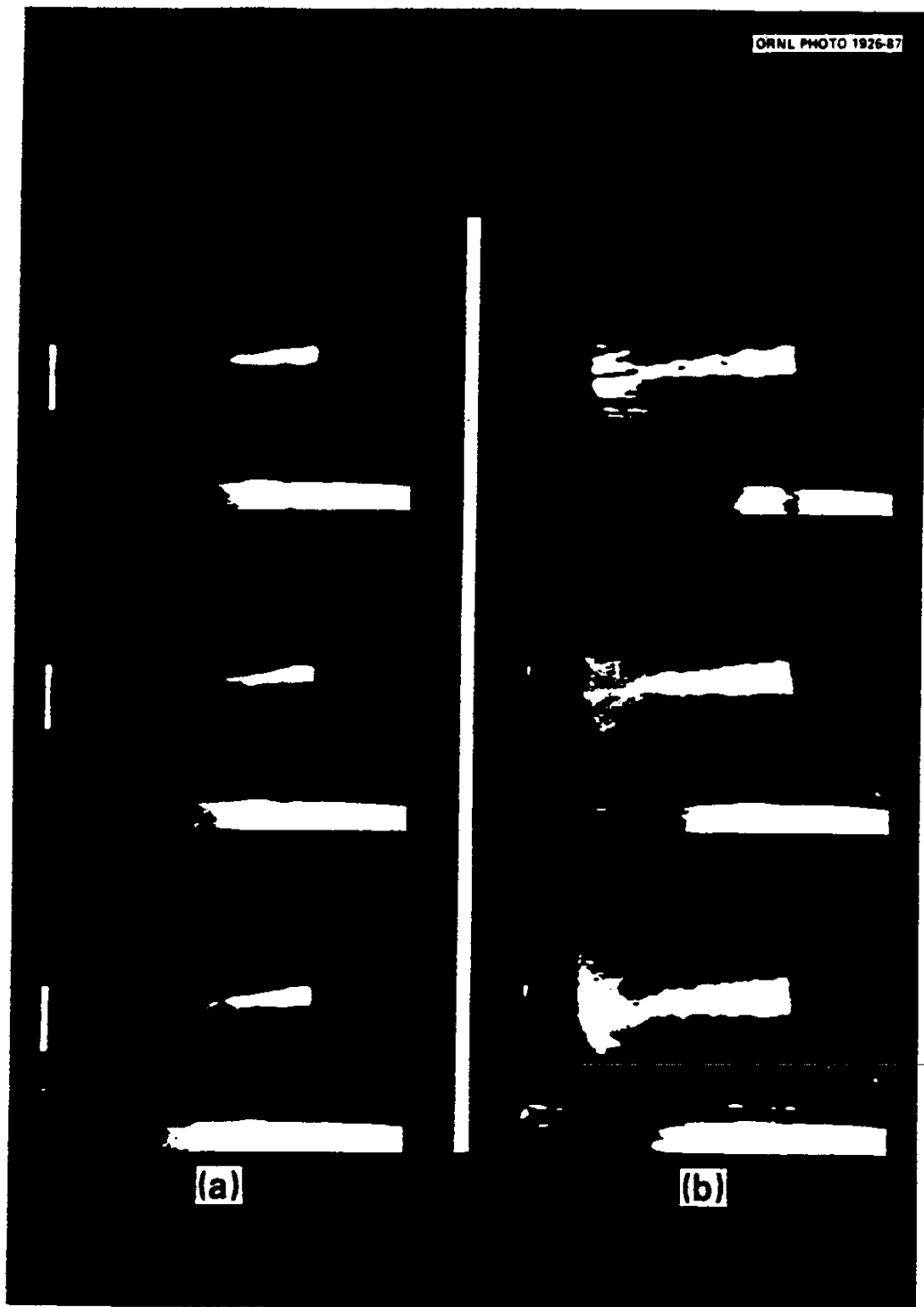


Figure 2.13 Three thermographs showing time sequence of engine exhaust gas thermal structure for an F100-PW-100 engine at (a) idle, and (b) slightly higher engine rpm.

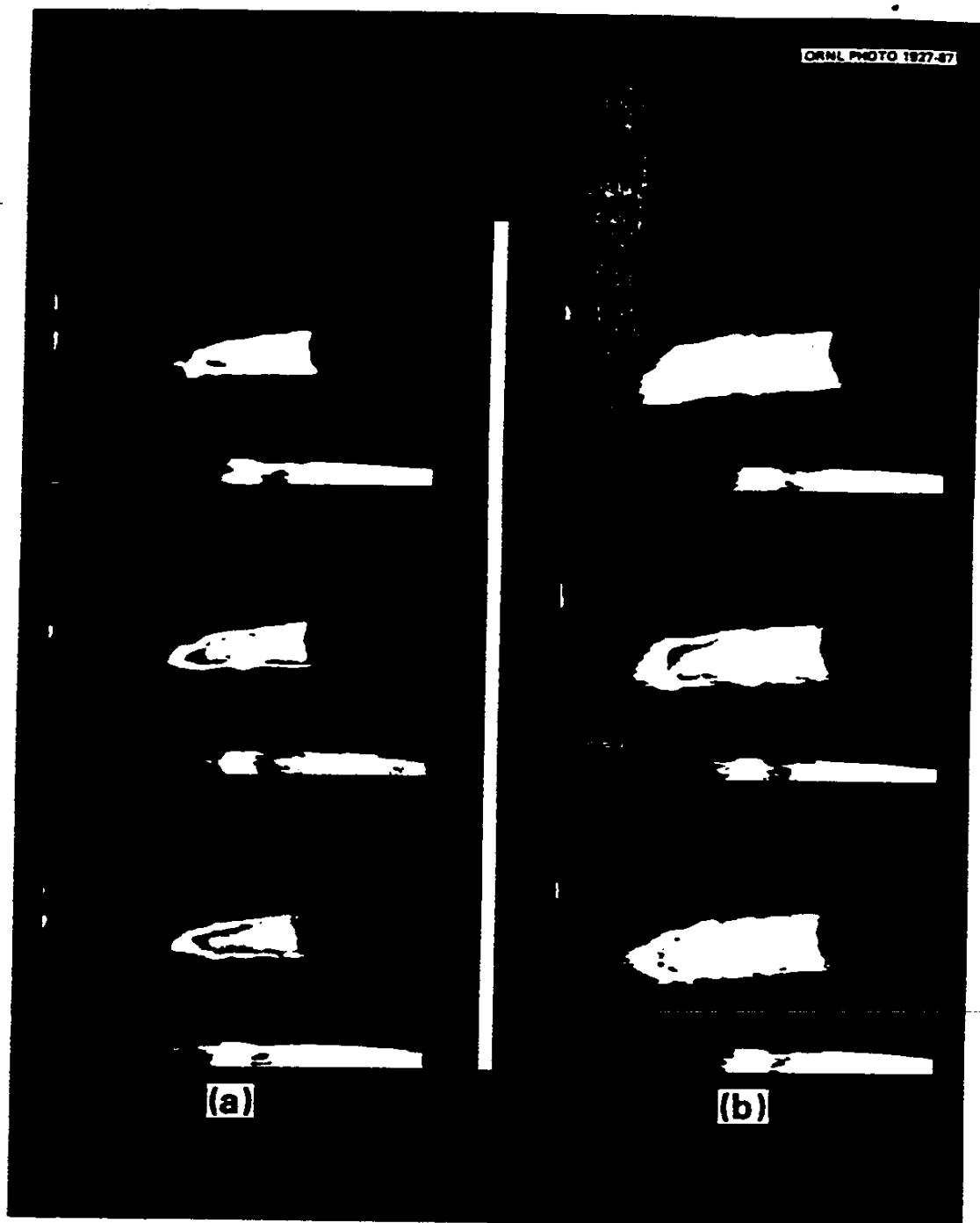


Figure 2.14 Three thermographs showing time sequence of engine exhaust gas thermal structure for an F100-PW-100 engine (a) near military power and (b) at full

Figure 2.14a is for either military power or the initial stage of afterburner, while Fig. 2.14b is for full afterburner. Vibration problems have occurred when engines are tested at these higher power levels. The thermal structure displayed in this figure is quite different from that of Fig. 2.13, but qualitatively similar to that produced by a radiating plume (Fig. 2.11). In this figure, the upstream portion of the plume is quite steady (no evidence of turbulent motions) and isotherms are close together and parallel to the axis of the plume. Small undulations at the edges of this portion of the plume are a result of the small amplitude self-excited wave. This portion of plume is producing acoustic Cherenkov radiation. The downstream portion of the plume displays features characteristic of turbulence. These images confirm the existence of acoustic Cherenkov radiation. The occurrence of vibration at nearby facilities at the same engine power levels at which visual evidence of acoustic Cherenkov radiation is reported provides strong support for the conclusion that the acoustic Cherenkov radiation is responsible for the low frequency emissions emanating from the hush house.

It is important to note that acoustic Cherenkov radiation is to be expected from the pure jet engines associated with the T-10 hush house function. The high bypass engines typically run in the T-9 hush house are not expected to generate significant acoustic Cherenkov radiation because there is only a small diameter high speed core flow and because the surrounding blow-by provides a more diffuse velocity gradient. The exception is the B1 engine which is the only pure jet engine currently in use in a T-9 hush house. This is the engine that failed the noise acceptance tests at McConnell AFB and Sky Harbor. .

The acoustic Cherenkov radiation which is generated within the hush house can be coupled to the environment through a resonant mode of the augmenter tube. The wavelength of an acoustic wave is equal to the ratio of the sound speed to frequency. The gas moving through the augmenter tube is at an elevated temperature, probably in the range of 400.-600.F. Since the speed of sound at 600.F is about 1600 fps, the wavelength of 10 Hz radiation at this gas temperature would be 160 ft (derived from the relationship: wavelength equals the ratio of sound speed to frequency). This is twice the length of the augmenter tube. It is well known that a cylindrical tube driven at one end will support a fundamental resonant mode having a

wavelength which is twice the length of the tube. This is known as the "organ pipe" mode. Thus, it is likely that this is the mechanism by which low-frequency energy is transmitted to the environment. This resonant mode produces a spherical wavefield characteristic of a virtual monopole source located approximately one tube diameter downstream of the tube exit. Analysis of the data collected at Luke AFB reveals that phase variations along the measurement contour are highly correlated with phase variations produced by a monopole source located at the deflector shield which is approximately one tube diameter downstream of the tube exit. This strongly supports the "organ pipe" mode hypothesis. Further support is provided by thermographic images taken of exhaust plume as it exits the augmenter tube. The spherical waves produced by a resonant phenomenon are the result of the spherical expansion and contraction of "puffs" of gas as they leave the augmenter tube. These puffs are advected downstream by the exhaust flow. Figure 2.15 is a thermographic image of the exhaust flow as it exits the hush house. The spherical waves produced by the resonant mode are evidenced by the obvious peristaltic shape of the isotherms.

2.2 Air Quality

From a historical perspective, potential air quality impacts by hush houses have become a concern as a result of a court ruling in a U.S. Court of Appeals case in California (State of California vs. Dept. of Navy, U.S. Court of Appeals, Ninth Circuit, 624 F. 2d 885 [June 2, 1980]). The ruling, in favor of California, found that hush houses should be treated as stationary sources, and as such must comply with applicable air quality standards rather than being exempt from standards as is the case with normal aircraft operations. Two air quality issues have been raised: concentrations of pollutants from the emissions and reduction of visibility due to the exhaust plume from the engine(s) during hush house operations.

Several studies (Lindenhofen et al., 1978; EPA, 1978) have been performed to evaluate air quality for the previous generation of engine test facilities at military installations called test cells. Hush houses are very similar to test cells from an air quality standpoint since the engines' emissions are the same and the design of the exhaust tube is similar. Air dispersion models which were run indicated that the test cells did not

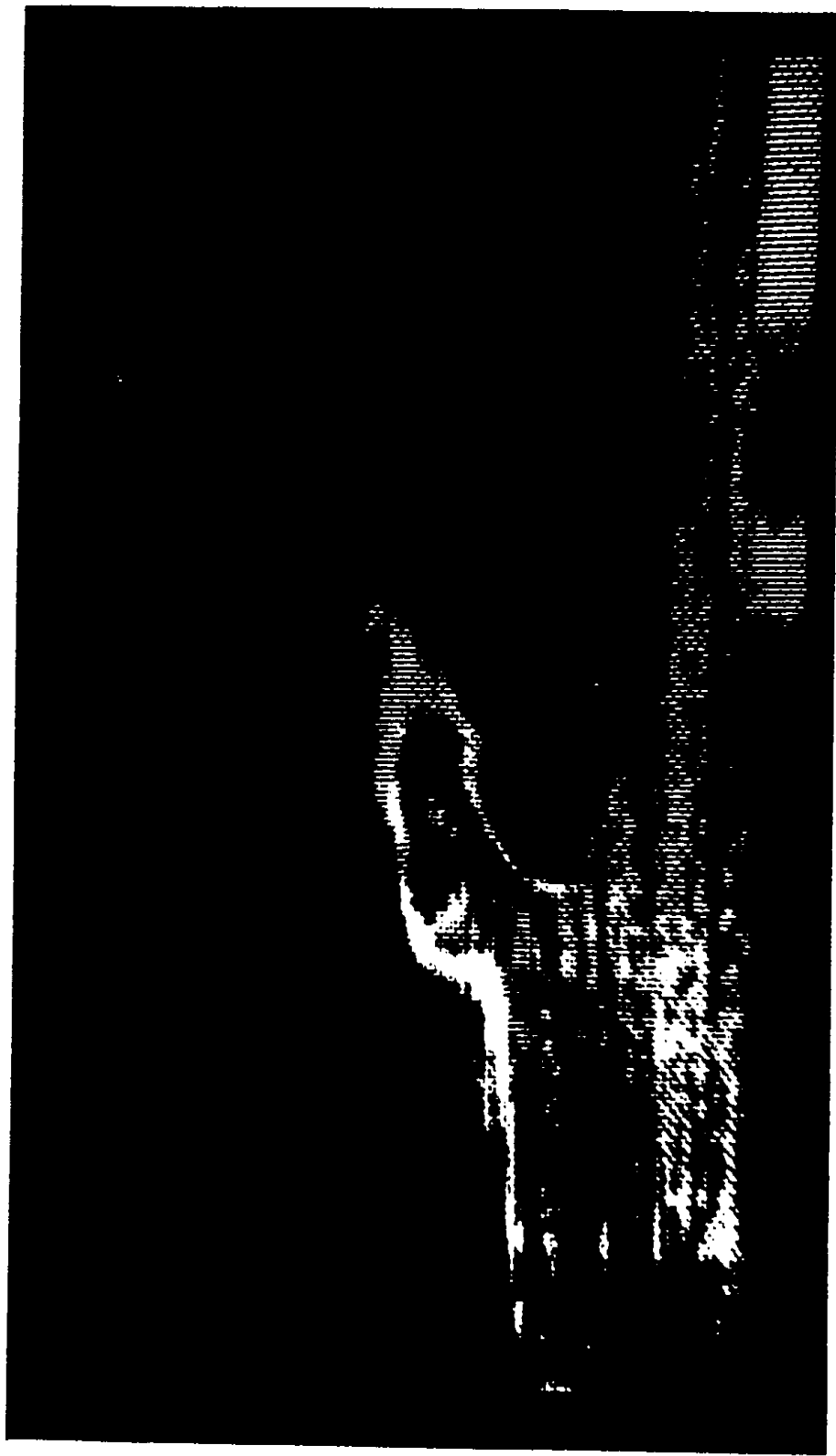


Figure 2.15. Thermographic image of exhaust gas as it exits the augmentor tube.

significantly affect ground-level concentrations of pollutants in the ambient air.

The exhaust plume from some of the engines in the test cells exceeded opacity standards, however. The older engines tended to emit more smoke and thus cause greater opacity. It was noted that violations occurred for only short periods during high power settings of the engines.

2.3 Land Use and Siting Criteria

The Air Force recognizes a need for hush house siting criteria that address the organizational and functional needs of jet engine maintenance and ensure land use compatibility with existing and prospective uses and buildings in the environs of hush houses.

For the convenience of the jet engine maintenance personnel and the users and operators of the hush house, these facilities should be located near or within a reasonable towing distance (1 mile) to the maintenance complex. Jet engines that are removed from the aircraft, mounted in a test frame, and towed for long distances are subject to damage of seals by foreign objects.

Hush house operational compatibility with existing and prospective land uses is an important determinant in hush house siting decisions. Four main constraints which influence hush house site location suitability are (U.S. Air Force, 1984b):

1. the noise source - the amount of energy emitted as a function of engine/aircraft types, power settings, and frequencies.
2. the noise propagation path - the path is dependent on site-specific environmental attributes.
3. the receptor response to noise - response of receptors plays an important role in the determination of effects on adjacent land uses.
4. the use of affected buildings - the adjacent land use function determines the sensitivity to noise emissions and hush house operations.

The impact on adjacent land uses from noise, infrasound, and induced vibration associated with hush house operation involves a complex interaction between the four factors listed above. Potential impacts are dependent, for example, on variables such as the

house, the frequency of hush house testing, basewide noise contours, local meteorological conditions, the distance between the hush house and adjacent land uses, the orientation of adjacent buildings relative to the hush house axis, adjacent building construction types, and the type of land use functions adjacent to the hush house.

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3. IMPACTS OF HUSH HOUSE OPERATION

3.1 Noise and Vibration

3.1.1 Noise

In order to establish the frequency dependent radius of influence for noise impacts for a variety of aircraft/engines and power settings, the following methodology is employed:

- (1) data for 7 aircraft, 6 engines, and 6 frequencies taken at a distance of 328 ft and adjusted to 250 ft from the center of the Texas ASE hush house (Lee, 1982) are used.
- (3) A de minimus impact level of 94 dB at 50 Hz, 91 dB at 100 Hz, 88 dB at 250 Hz, 84 dB at 500 Hz, and 83 dB at 1000 Hz (U.S. Air Force, 1983) is assumed and the distances from the center of the hush house at which these levels are achieved are computed by conservatively assuming that sound pressure levels from the 250 ft contour vary as the inverse of the square root of the distance.
- (2) it is assumed that no angular dependence exists and for each frequency and power setting, sound radiates uniformly at all angles. The maximum value on the 250 ft radius contour is conservatively assumed for all directions.

Table 3.1 presents these computed values at 50 Hz. For the higher frequencies, the maximum acceptable sound pressure levels were not exceeded beyond 250 ft. It is clear from this table that excessive sound pressure levels beyond 250 ft from a hush house are limited to low frequencies (50 Hz or below), a small number of aircraft/engines, and afterburner mode. During normal trim operations, the duration of afterburner is short, typically 20 seconds.

Audible Noise As discussed earlier, each hush house must undergo acceptance testing. Acceptance criteria with respect to noise abatement is that the Aweighted noise level not exceed 89 dB at any of the twenty or more specified measurement points on the near circular, 250 ft radius contour as shown in Figure 1.7. This level of 89 dB(A) is near the onset for inducing a small hearing loss if persons are exposed over a long period of time (Baughn, 1973; Burns and Robinson, 1970). Peak levels produced during afterburner operation persist for such a short time that hearing loss is not an issue at locations external to the 250 ft measurement contour. In addition, existing Air Force regulations (U.S. Air Force, 1982)

Table 3.1. Distance, in feet, beyond which sound pressure levels at 50Hz do not exceed 94 dB.

<u>Aircraft/ Power setting</u>	<u>50Hz</u>
F-4/85%	-
F-4/MP	-
F-4/AB	-
F-15/MP	-
F-15/AB	396
F-16/MP	-
F-16/AB	315
F-105/90X	-
F-105/MP	-
F-105/AB	673
F-106/85Z	-
F-106/90%	-
F-106/MP	-
F-106/AB	1253
F-111F/85%	-
F-111F/95X	-
F-111F/MP	-
F-111F/AB	995
T-38/MP	-
T-38/AB	-
 <u>Engine/ Power setting</u>	
TF-41-A-1/MP	-
TF-41-A-1/MMP	-
J79-GE-15/MP	-
F100-PW-100/80X	-
F100-PW-100/MP	-
F100-PW-100/AB	1986
J75-P-19/91%	-
J75-P-19/MP	396
J75-P-19/AB	3962
J75-P-17/90%	-
J75-P-17/MP	-
J75-P-17/AB	1253
TF30-P-100/85X	-
TF30-P-100/MP	-
TF30-P-100/AB	1986

Based on data from Lee(1982) measured at 328ft. and adjusted to 250ft.

% indicates percent of maximum rpm.

MP indicates military power.

MMP indicates maximum military power.

standards, assigns responsibilities, provides for a monitoring program, and directs effective coordination of Air Force activities in noise abatement.

The primary function of the hush house is, in fact, abatement of audible noise. The T-10 hush house clearly accomplishes this objective by reducing noise levels to below 89 dB(A) at a distance of 250 ft directly behind the augmentor tube even with afterburner operation. Noise reduction has been achieved at the two operational T-9 hush houses, however, half of the eight engines tested at McConnell AFB and the only engine tested at Sky Harbor IAP failed to meet the noise level acceptance criteria. Clearly, locations closer than 250 ft from a T-10 hush house would be subject to noise levels in excess of 89 dB(A) for short periods of time, primarily when testing at full power or in afterburner mode. The fraction of time in this mode is rather small and it is not anticipated that audible noise will be a siting constraint beyond 250 ft for hush houses in terms of potential hearing loss.

3.1.2 Infrasound

The hush house transfers considerable energy from the audible to subaudible range. This is demonstrated clearly in Fig. 2.1 in which the sound pressure level of noise from the hush house is seen to increase monotonically from 1000 Hz to the range of 1520 Hz. At these lower frequencies, the human ear is very insensitive to the infrasound because the wavelengths are too great for the sensory receptors to be activated sufficiently for people to notice unless the intensities are quite high. At a 250 ft radius from the hush house the sound pressure levels at 50 Hz and below can be in excess of 100 dB (Table 2.1). Thus, there is a need to examine the literature to determine whether or not any adverse effects of infrasound on human health would be sufficient to cause a siting restriction. Infrasound can act directly or it can act by way of startle or annoyance, e.g., induction of vibrations in doors, windows, or other structural elements, etc. The only difference between infrasound and vibration is the receptor mode. If the receptor receives air coupled vibrations they are generally considered infrasound, but if the receptor receives sound transmitted through solids, they are vibrations.

Firstly, as a matter of perspective, infrasound, comprised of frequencies below about 16 Hz is present to a large extent in the day to day world (EPA, 1973). Westin (1975) has

different natural infrasound sources with sound pressure levels between 75-95 dB; these include storms, tornadoes, auroral discharges and ocean waves, volcanic eruptions, earthquakes, and lightning discharges to name a few. Most of these natural sources have a characteristic frequency less than 1 Hz. Man-made infrasound has also been shown to be present, sometimes at high pressure levels. Most of the man-made infrasound occurs between 1 and 15 Hz and derives from machinery. For example, levels inside an automobile traveling between 40 and 70 mph have been measured as high as 120 dB in the 2-4 Hz range (Westin, 1975). However, infrasound is rarely present in excess of 125 dB (Kryter, 1970). Little is known about whether low frequency noise is harmful or not (Broner, 1978). In general, exposure to infrasound as high as 140 dB has been recognized as being safe (Harris et al., 1976; Slarve and Johnson 1975). This perspective is supported by literature reviews (Harris et al., 1976; Slarve and Johnson 1975) as well as controlled laboratory studies (Mohr et al., 1965; Slarve and Johnson, 1975; Harris and Johnson, 1978). In these reviews, the question of "safe" primarily involves consideration of acute effects, and especially nystagmus, which is spasmodic, involuntary motion of the eyeball. The symptoms of nystagmus are similar to the effects of alcoholic intoxication, including impaired balance and cognitive performance. These symptoms, if produced by moderate levels of infrasound, could result in limiting siting criteria of hush houses because of possible interference with normal human function.

The possibility of nystagmus has been examined thoroughly through literature review and by performing controlled laboratory tests. This conclusion comes from a review of the pertinent literature (Harris et al., 1976). Much of the available literature on potential acute effects is flawed by the use of small numbers of subjects, "sensitive" subjects, lack of controls, and lack of intensity measures, etc. Nixon and Johnson (1973) have suggested that the maximum exposure limit for infrasound for a 24 hour period be 133 dB at 1 Hz, 126 dB at 5 Hz, 123 dB at 10 Hz, and 120 dB at 20 Hz. No contradictory limits to these have been found. Under these criteria, no siting restrictions based on potential acute health effects would be anticipated beyond the 250 ft measurement contour.

In addition to potential acute effects, the possibility for chronic effects resulting from long term exposure to infrasound must be examined. Harris et al. (1976) is rather emphatic that chronic nystagmus symptoms at

the low intensity levels of 105 to 120 dB, if they can be substantiated at all, have been exaggerated. Recently, several investigators have examined cardiovascular function in persons exposed to infrasound (Danielsson and Landstrom, 1985; Martinek and Opitova, 1986). The reasoning behind these investigations is that noise is considered to be an environmental stress factor (Selye, 1979). Most previous investigations concerning effects of noise exposure on blood pressure have, in general, dealt with noise of broad band frequencies, not distinguishing between low-frequency (infrasound) and sound within the normal hearing range. Epidemiologic studies using this broadband exposure have resulted in mixed, but mostly negative results (Jonsson and Hansson, 1977; Drettner et al., 1975; Takala et al., 1977; Malchaire and Mullier, 1979; Thompson, 1983; Kent, von Gierke and Tolar, 1986).

Two different measures of altered cardiovascular functions resulting from infrasound exposure have been obtained recently. Danielsson and Landstrom (1985), using 16 Hz infrasound, have measured significantly decreased systolic and increased diastolic blood pressures with 9S and 125 dB exposure without any rise in pulse rate. The increase in diastolic blood pressure reached a maximal mean of 8 mm Hg after 30 min exposure. Since no increase in pulse rate was detected, a rise in peripheral vasoconstriction was inferred. A different trend of slightly increased systolic blood pressure, decreased diastolic pressure along with increased heart rate was described by Martinik and Opitova (1986), who used 12.5 Hz infrasound at 100 dB. 80% of these studies are unduplicated and some of the experimental conditions are not clear. It is thus not possible to make decisions on the basis of these two reports. However, effects were reported only above 9S to 100 dB. At 250 ft directly behind the augments tube, these levels and above would only be present during the short bursts of afterburner testing. It may be argued that such short exposures, leading to possible short-term changes in cardiovascular function of approximately 5% would result in negligible long-term consequences. Lacking clear evidence of an adverse effect of infrasound exposure to 90-100 dB on cardiovascular function, the application of strict land use controls within 250 ft of a hush house appears to provide adequate personnel protection. Lacking additional information, two alternative options present themselves; (1) maintain a 9S-100 dB exclusion zone for long-term exposure to infrasound, (2) monitor personnel for changes

in cardiovascular function. The first option appears to be the prudent one and is ensured by the 250 ft measurement contour.

3.1.3 Vibration

The magnitude of structural vibrations driven by airborne waves will be influenced by many parameters including: frequency and amplitude of the wave and the orientations of its propagation vector relative to the structure, the mass per unit wall area and wall compliance (flexibility) per unit width of the structure, the means by which the structure is anchored to its foundation, and area of the walls of the structure which are exposed to the airborne waves. In order to quantify the relative influence of these parameters, the response of a model, infinite wall is investigated. The model wall is represented by its mass per unit area, m , stiffness per unit width, S , and anchoring spring constant per unit width, K . The incident wave is taken to be planar and oblique, described by a frequency, f , and propagation angle, θ , relative to the axis of the wall. This model wall is depicted schematically in Fig. 3.1. The response of the wall, F , is derived as a function $F(m, k, S, f, \theta)$ in Appendix A and is defined by the relation

$$V_w = F V_j,$$

where V_j and V_w are the harmonic velocities of the incident airborne wave and the induced wall wave, respectively.

The response function is used to investigate the influence of construction type and distance from the hush house on building vibrations. It is assumed that the velocity of the low frequency pressure wave emanating from the hush house decays as spherical wave. Of the three wall parameters m , S , and K , the mass per unit area, m , is the only parameter which is easily estimated. As a worst case with respect to structural impacts, S and K can be ignored (taken as zero). When considering a rectangular structure, decreasing the incident angle for one wall will increase it with respect to an adjacent wall. Consequently when considering the impact to an entire structure, only directions of incident wave propagation with angles between 45° and 90° with respect to the wall need to be considered. For example, a rectangular block structure with one wall parallel to the plane of the incident wave (i.e., a wall which is perpendicular to the direction of the

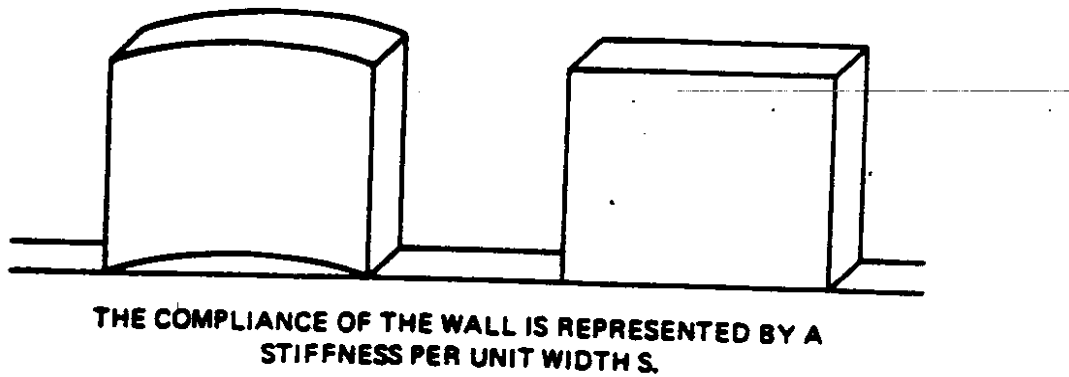
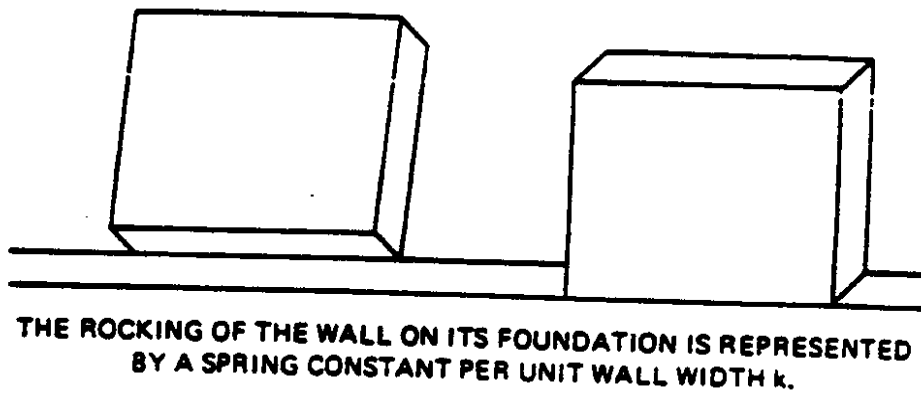
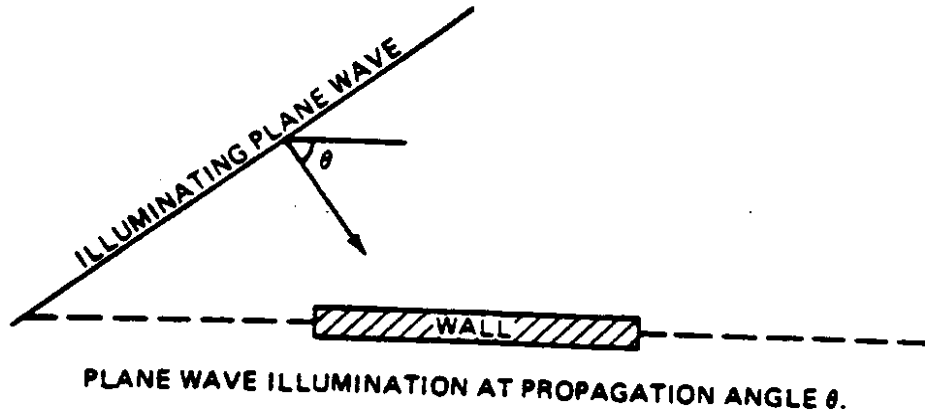


Figure 3.1. Illustration of wall motion mechanisms included in the infinite wall model.

incident airborne wave) will experience vibrations in that wall only. Rotating the structure by 45° will result in vibrations to two adjacent walls but at levels lower than those for the parallel wall case. The wall response, neglecting the wall stiffness and spring constant ($S \sim K \cdot 0$), is used to estimate distances beyond which a specific wall acceleration is not exceeded (see Appendix B). These distances are given as a function of wall acceleration in Table 3.2 for concrete block, wood frame, and pre-engineered metal walls at both 90° (normal incidence) and 45°. For vibration sensitive functions, maximum tolerable accelerations are 10^{-3} to 10^{-4} g (U.S. Air Force, no date). As can be seen in Table 3.2, concrete block walls can satisfy the most stringent requirement beyond about 500 ft from the hush house if the walls which are exposed to the infrasound have no windows or doors. This table also shows that vibrations are far more severe for wood frame and preengineered metal walls. While the model used to estimate wall accelerations is inexact as a result of the simplifying model assumptions, it is expected that this model properly represents trends. It can be concluded that vibration sensitive functions should either be restricted to structures with at least one solid concrete block wall (the wall facing the hush house) or these functions should be located at considerable distances from the hush house.

Table 3.2. Distance (ft) beyond which the wall acceleration is below the indicated value. Normal incidence for the pressure wave is 90°.

	<u>acceleration (g.)</u>		
	10^{-4}	5×10^{-4}	10^{-3}
concrete block (90°)	460	---	---
concrete block (45°)	472	---	---
wood frame (90°)	7,826	1,565	783
wood frame (45°)	6,800	1,360	680
prefab metal (90°)	10,600	2,120	1,060
prefab metal (45°)	8,100	1,620	810

The consideration of structural vibrations thus far has been limited to walls of infinite extent. An important mode of structural response which is associated with walls of finite dimension is resonance. Strong coupling

between a wall and the incident wave will occur when the frequency of the incident acoustic wave is near the natural frequency of a wall or other structural component of the building. Natural frequencies for building walls or other substructures range from 10 to 50 Hz for low rise structures (ANSI, 1983). This frequency range falls within the most energetic region of the hush house emission spectrum (Fig. 2.1) indicating that resonant forcing is a potentially significant impact of hush house operations. While it is beyond the scope of this study to quantify induced vibrations in structures of finite dimensions, considerable insight may be gleaned from the infinite wall model. It can be seen from Eq. (9) of Appendix B that the wall response function becomes infinite when the angular frequency equals the square root of the ratio of the restoring force to the mass per unit area of the wall. This behavior indicates that this particular frequency is a resonant frequency of the wall. In reality, the wall response is not infinite, but an artifact of the linear wall model; however, it reflects the fact that maximum wall response will occur at or near the resonant wall frequency.

Two additional points must be considered in the discussion of structural vibrations. First, the above discussion applies to inclusions in exterior walls as well as to homogeneous exterior walls. Even though a solid exterior wall such as one made from concrete blocks is not particularly susceptible to induced vibrations, inclusions such as doors and windows may exhibit significant forcing (vibrations). Windows, which typically are loosely anchored and are characterized by a small spring constant K , are prone to rattle. The second point is that exterior walls, characterized by a large response function are highly transmissive to wave energy. Thus, an exterior wall that exhibits strong wave induced vibrations will also transmit significant wave energy to the interior of the structure which could result in vibrations of interior walls, tables cabinets, etc. Both of these effects have been observed in the crash fire station at Otis AFB. This is a concrete block structure in which considerable frontal area is occupied by windows and large sheet metal doors. While no significant vibrations could be detected in the exterior block, the interior noise level was quite loud as a result of the rattling of doors and windows. The window and door area allowed the transmission of enough wave energy to cause detectable vibrations of the interior sheet rock walls.

Physical impacts of vibrations are structural damage and functional interference. Although guidance exists for establishing vibration impacts, it is not possible to precisely quantify the impacts of hush house operation using the limited quantitative information that is available. Threshold accelerations of 10^{-3} to 10^{-4} g for functional interference at precision measurement equipment laboratories (PMEL) and at avionics laboratories have been suggested (U.S. Air Force, no date). Table 3.2 indicates that minimum distances beyond which interference with function will not occur could be as close as 800 ft or as far as 11,000 ft for pre-engineered metal buildings. As a qualitative portrayal of the influence of building construction type and orientation relative to the hush house, this 800-11,000 ft range is not unrealistic in light of the many complexities of the problem. Induced vibrations depend upon construction type, frequency of incident wave, wall area exposed to compressional wave energy, etc. Consequently, 800 ft may be a reasonable distance for a small, single story, pre-engineered building beyond which interference with function will not occur. Similarly, the 11,000 ft distance could be reasonable for large, multistoried pre-engineered buildings.

An acceleration of 0.01 g is recommended as a threshold for structural impacts (Bolz and Tuve, 1976), however, it can be argued that the threshold acceleration should depend upon the construction type. Massive and rigid structures, such as concrete block will experience relatively low acoustic wave induced vibrations, although, the relatively small compliance of such materials will make them susceptible to damage. On the other hand, building composed of lighter and more compliant materials (e.g., corrugated steel sections) will experience considerably greater wall acceleration, but the greater flexibility of this material makes it less prone to vibration-induced structural damage. Thus, structural impacts are, to some extent, less sensitive to construction type and more strongly dependent upon pressure loading. Consequently, the greatest potential for structural damage occurs for multi-story structures with significant wall areas exposed to incident wave. While steel wall panels are not particularly susceptible to vibration induced damage (due to their flexibility), buildings composed of this material are at greater risk as a result of induced wall motions loosening structural fasteners. Vibration induced structural impacts have been

reported within 500 ft of an operating hush house for a brick building and as far away as 1000 ft for pre-engineered meta1 buildings.

There is little potential for direct infrasound absorption to produce vibrations in the human body. There is very little absorption of acoustic energy by the human body -- about 2% at 100 Hz according to von Gierke (1950). However, when infrasound interacts with solid objects and induces vibrations, individuals can be subject to startle arousal and annoying noise. For example, significant vibrational energy can be transmitted from building-to chair-to-person. A rather considerable body of literature is available relating comfort and performance to vibrations, and many studies have been performed examining potential health effects from prolonged exposure to vibrations of large amplitudes and accelerations. At the present time it remains unclear to what extent whole-body vibration does constitute a health hazard.

Vibration in buildings can interfere with activities and affect human occupants in different ways. There are many and complex factors determining human response to vibration, and a lack of consistent quantitative data concerning human perception and reaction to it. Both national (ANSI, 1983) and international (ISO, 1974) standards have been developed to provide provisional recommendations on satisfactory magnitudes with respect to human response to vibration in buildings.

The EPA (EPA, 1982) has provided guidance based on the national and international standards. Basically, the highest standards (lowest vibrations-levels) are required for residences or especially sensitive areas such as hospital operating rooms. This is characterized by an absence of perceptible vibration. Under other conditions, such as offices, manufacturing areas, etc., there may be some tolerance to vibration disturbance. EPA guidance is represented in Fig. 3.2.

The accelerations presented in the figure are weighted to account for the variation of human sensitivity as a function of vibration frequency as well as direction. In the present case, the vertical or z-axis values will be used in order that the analysis would not underestimate human responses. No direct vertical displacements would be expected from the plane wave propagating from the hush house, however the frequency distribution of the source overlaps with resonant modes of buildings. Thus there is significant likelihood that resonant modes of a building would be driven by the

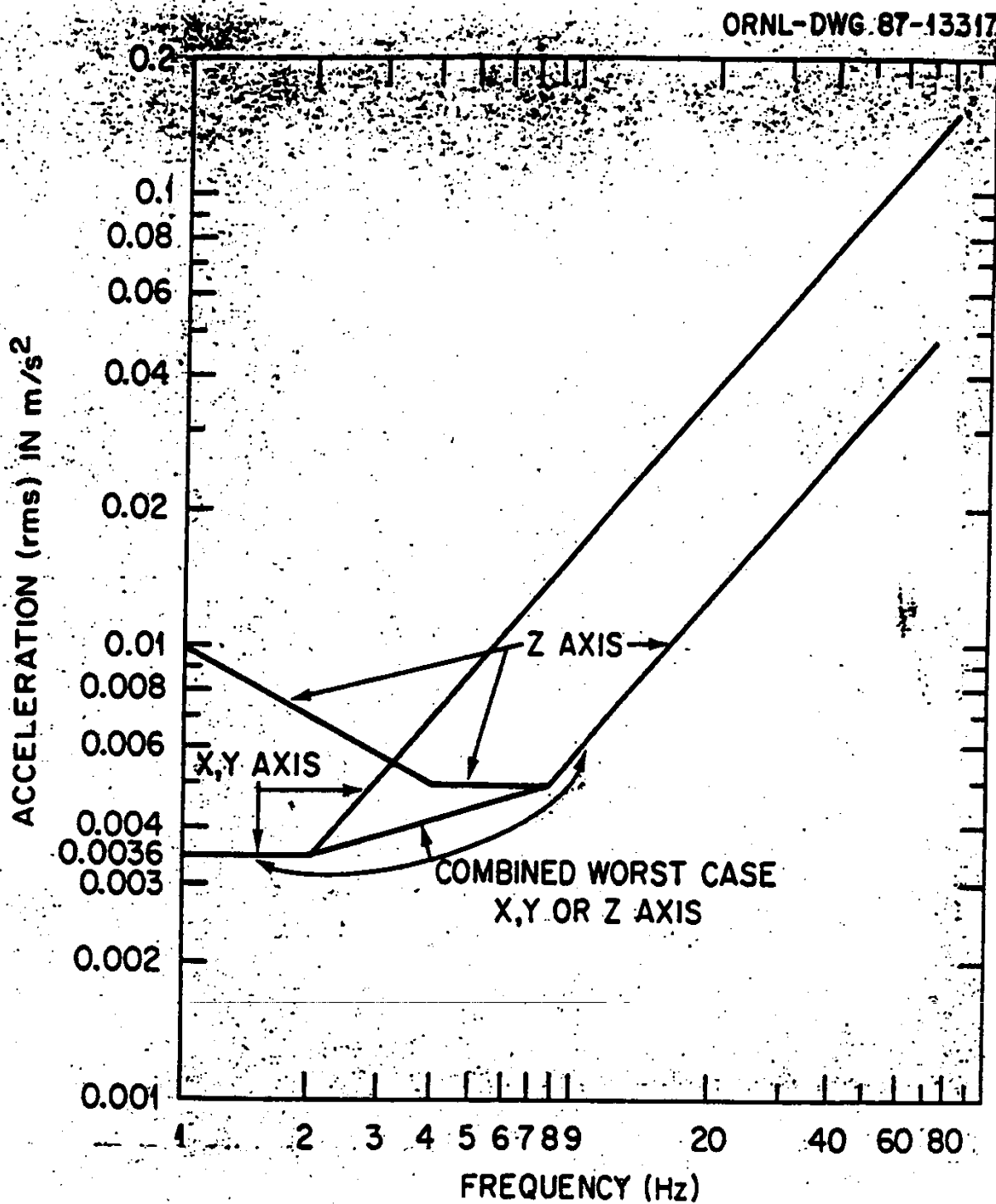


Figure 3.2. Building vibration criteria for occupants in buildings. A11 curves are for hospital and critical working areas [Source: EPA, 1982]

infrasound propagating from hush houses. If this is true, then significant vertical motion will occur. One further consideration which is quite important has to do with building occupant function. The EPA (1982) has provided a set of multiplicative weighing factors which allow for differential sensitivity by function: hospital operating theatre and critical working areas -- 1; residential day -- 2, night -- 1.4; office -- 4; and workshop -- 8. These weighing factors were derived largely from data from controlled experiments.

It should be noted that the ISO standard contains exposure duration factors but does not have universal agreement particularly with regard to the role which exposure duration or frequency of occurrence plays in the recommended levels. Specifically, the ISO standard was developed at a time when temporal data were sparse and Osborne (1983) implies that discomfort as a function of exposure duration is overestimated. Some new evidence is emerging which may bear out this possibility (Kjellberg et al., 1985). The potential effect of this overestimation of the discomfort with prolonged exposure is that the guidelines or standards will be too restrictive. For hush house operation, only when the test engines are in afterburner mode is there a significant potential for induced vibrations. These events are short (approximately 20s), and occur only a few times per day. Therefore, no attempt will be made to incorporate the effects of exposure duration on siting criteria.

3.2 Air Quality

Potential air quality impacts caused by emissions during hush house operations have been identified for two issues: concentrations of air pollutants and reduction of visibility. These issues were investigated to quantify their actual impact. Both issues are dependent on the type of engine which is being tested in the hush house.

Potential impacts due to concentrations of air pollutants were assessed in terms of comparisons to applicable air quality standards. The standards have been established for ground-level concentrations of pollutants in the ambient air. Ambient air is defined to include the entire area outside of the military installation and often includes base housing (depending on the governing regulatory agency).

Air dispersion modeling was performed to estimate maximum groundlevel concentrations resulting from air pollutants emitted during hush house operations. The PTMAX model, part of the U.S. Environmental Protection Agency's Users' Network for Applied Modeling of Air Pollution (UNAMAP) series (EPA, 1986), was used in the modeling runs. PTMAX employs a steady-state Gaussian plume equation to calculate maximum concentrations for many combinations of atmospheric stability and wind speed. While a specific site was not specified for the modeling, PTMAX assumes that the terrain is relatively flat. The following data were provided as input to the model: emission rate of the pollutant, physical height and diameter of emission release, emission velocity and temperature, and ambient air temperature.

The input data are dependent on the type of engine operating in the hush house. Emission rates of pollutants were estimated using the Aircraft Engine Emissions Estimator (Seitchek, 1985) for all engines potentially being tested in a T-9 or T-10 hush house. Emission velocities and temperatures were estimated at the point of release to the environment (at the deflector shield) using performance curves that have been established for the engines. The estimates were spatial averages that weighted the centerline values with values at the perimeter (along the inside wall of the exhaust tube) at the point of release.

The spatially-averaged emission velocity required an adjustment because the initial direction of the exhaust leaving the deflector shield is 45 degrees from vertical, while the PTMAX model expects an initial vertical velocity. The initial velocity was separated into horizontal and vertical components. The vertical component was used as input to the model, and the horizontal component was used to calculate a spatially-averaged horizontal displacement distance of concentrations along the axis of the exhaust tube.

Engine performance curves were used to estimate the displacement distance by assuming the displacement was equal to the distance at which the centerline horizontal speed became less than 10 mph. This displacement distance can be represented as a vector that should be used to adjust the location of the maximum groundlevel concentration computed by PTMAX, which is positioned on the downwind axis. For example, if the wind direction is parallel to the axis of the exhaust tube, then the location is simply moved further from or closer to the hush house along the downwind axis, depending on whether the wind is blowing with or against the initial horizontal

component, respectively. For other wind directions, the vector adjusts the location so that it no longer is positioned on the downwind axis. A typical value for the spatially-averaged horizontal displacement distance, estimated for the F100-100 engine at military power, is 260 ft.

The PTMAX model was run to estimate concentrations for three of the six criteria pollutants for which National Ambient Air Quality Standards (NAAQS) have been established: carbon monoxide (CO), nitrogen dioxide (NO₂), and particulate matter. The other three criteria pollutants (sulfur dioxide, lead, and ozone) were not modeled. Sulfur dioxide and lead emissions during hush house operations are negligible. Ozone concentrations from a single source cannot be quantified, since ozone occurs on a regional scale associated with many sources as a result of complicated reactions involving hydrocarbons, nitrogen oxides, and sunlight.

The model was run for a variety of engine types at two power settings: military power and afterburner mode (for applicable engines). Maximum groundlevel concentrations were compared for the two settings. Table 3.3

Table 3.3. Emission rates and concentrations for the F100-100 engine during military power and afterburner mode.

	Emission Rate (g/sec)	Maximum Ground-Level Concentration (ug/m³)
Carbon Monoxide		
Military Power	1.17	2.3
Afterburner Mode	23.20	3.5
Nitrogen Dioxide		
Military Power	35.10	69.0
Afterburner Mode	17.98	2.7
Particulate Matter		
Military Power	0.44	0.9
Afterburner Mode	0.87	0.1

displays emission rates and concentrations of the three pollutants for the F100100 engine. Integral concentrations were usually lower during afterburner mode for NO2 and particulate matter because of greater plume rise associated with the higher exhaust temperatures and velocities which lifted the plume centerline further from the ground. The emission rate of these two pollutants at the engine exhaust was usually very similar for the two power settings because the increased fuel flow in afterburner mode was offset by the decreased amount of pollutants per mass of fuel.

Ground-level concentrations of CO were usually slightly higher during afterburner mode due to the large increase in the CO engine emission rate, which more than counteracted the higher exhaust temperatures and velocities that increased plume rise. Because concentrations during afterburner mode were not significantly higher, and because testing in afterburner mode occurs for a total duration of only about two minutes during a standard test, afterburner mode was not considered further in the evaluation of air quality effects.

Table 3.4 lists maximum ground-level concentration of CO, NO2, and

Table 3.4. Comparison of concentrations with National Ambient Air Quality Standards (NAAQS) for several engines during military power.

Engine	Emission Rate (g/sec)	Maximum Ground-Level Concentration (ug/m ³)	NAAQS (ug/m ³)
Carbon Monoxide			
J79-17	6.45	13	40,000 (during 1 hour)
F101-100	9.58	19	10,000 (during 8 hours)
Nitrogen Dioxide			
F100-100	35.10	69	470 (1-hr Calif. Std)
F103-100	89.42	176	100 (annual mean)
Particulate Matter			
J79-15	2.46	5	150 (during 24 hours)
J57-43WB	1.71	3	60 (annual mean)

particulate matter that were predicted for several engines at military power, and the corresponding NAAQS. The engines were selected because of their relatively large emission rate for the given pollutant. The first engine listed for each pollutant is tested in T-10 hush houses and the second in a T-9 hush house. The concentrations are for testing of a single engine. For multiengine fighter aircraft, tests are typically performed with only one engine operating or for one engine at idle while the other operates at varying power settings. Thus, the potential contribution of a second engine to air quality emissions is minor.

A comparison of concentrations to N M Q S reveals that the concentrations of CO and particulates are a small fraction of the standards. Comparisons are most valid with 1-hr standards to correspond with the short averaging time of maximum concentrations predicted by the model and the intermittent nature of hush house operations. But the concentrations produced during hush house operations are also significantly less than the 8-hr CO standard and the 24-hr and annual mean particulate standard. NO₂ concentrations are roughly at the same level as the annual mean standard for NO₂, which is not a fair comparison. The State of California, however, has a 1-hr standard for NO₂ at a level of 470 ug/m³; the NO₂ concentrations are considerably less than this standard.

It should be noted that results from the PTMAX model indicate that there is no critical distance beyond which concentrations drop rapidly for all meteorological conditions. For example, although a worst-case maximum concentration may occur under neutral atmospheric stability and high wind speeds at a distance of 0.6 miles, a maximum concentration for stable conditions and moderate wind speeds can occur at a distance of 6 mi at a level which is half of the worst-case maximum. Table 3.5 provides an example of this for the F100-100 engine at military power for CO; the table lists maximum ground-level concentrations and the corresponding distances and plume heights for a variety of wind speeds and atmospheric stabilities. This sensitivity of maximum concentrations on distance varies somewhat depending on the engine being tested. But overall, from the standpoint of ground-level concentrations, the distances between the hush house and the nearest fence line (beyond which the standards apply) is not a critical factor in the siting of hush houses.

Table 3.5. Maximum groundlevel concentrations of Carbon Monoxide and corresponding distances and plume heights for a variety of wind speeds and atmosphericstabilities in tests of the F100-100 engine at military power.

Atmospheric Stability Class	Wind Speed (m/sec)	Maximum Ground-Level Concentrations (ug/m³)	Distance of Maximum (miles)	Plume Height (ft)
1 (Unstable)	1.5	0.9	0.7	2280
1	2.0	1.0	0.6	1706
1	2.5	1.0	0.6	1365
1	3.0	1.2	0.5	1138
2	1.5	0.4	2.5	2277
2	2.0	0.5	2.0	1706
2	2.5	0.5	1.6	1365
2	3.0	0.6	1.4	1138
2	4.0	0.8	1.1	853
2	5.0	1.0	0.9	682
3	2.0	0.3	4.5	1706
3	3~0	0.5	2.9	1138
3	5.0	0.8	1.6	682
3	7.0	1.1	1.1	489
3	10.0	1.5	0.7	341
3	12.0	1.8	0.6	285
3	15.0	2.3	0.5	226
4 (Neutral)	2.0	0.1	29.0	1706
4	3.0	0.1	14.4	1138
4	5.0	0.3	6.0	682
4	7.0	0.5	3.5	489
4	10.0	0.9	1.9	341
4	15.0	1.5	1.1	226
4	20.0	2.3	0.7	171
5	2.0	1.3	6.2	446
5	3.0	1.3	4.9	387
5	4.0	1.3	4.1	354
5	5.0	1.2	3.6	328
6 (Stable)	2.0	1.0	12.5	371
6	3.0	1.2	8.9	322
6	4.0	1.2	7.3	292
6	5.0	1.2	6.2	272

A related air quality concern regards whether a proposed hush house would emit pollutants in quantities that exceed a source limit, thereby qualifying the hush house as a major source. If so, it is subject to New Source Review, which contains further standards such as Prevention of Significant Deterioration (PSD) increments in regions that are in compliance with N M QS. PSD increments establish maximum allowable increases in ambient air concentrations over baseline values for SO₂ and particulate matter. If a proposed hush house subject to New Source Review is to be located in an attainment area for N M gS, necessary offsets of emissions would need to be obtained from existing sources in order to operate the hush house.

The frequency and duration of hush house operations which would maintain emissions within the source limit vary according to the pollutant and type of engine being tested. NO₂ is the pollutant most likely to exceed the limit. Generally, however, hush houses are not expected to exceed the source limit during normal testing. In the event a hush house would be subject to the PSD process, a comparison of PSD increments versus maximum ground-level concentrations estimated by the PTMAX model for particulate matter indicates that concentrations should be much less than the PSD increments, especially when considering that the standards are set for longer averaging times. Table 3.6 displays the comparison for two of the engines with relatively high

Table 3.6. Comparison of concentrations with Prevention of Significant Deterioration (PSD) increments for particulate matter (military power).

Engine	Emission Rate (g/sec)	Maximum GroundLevel Concentration (ug/m ³)	<u>PSD Increment (ug/m³)</u>	
			Class I Area	Class II Area
J79-15	2.46	5	10 (24 hours)	37 (24 hours)
J57-43WB	1.71	3	5 (annual)	19 (annual)

emission rates for particulates. Note that Class I areas (e.g., wilderness areas) allow less degradation of the ambient air than Class II areas, which essentially are all other areas.

The second air quality issue concerns the reduction of visibility due to the exhaust plume from the engine(s) during hush house operations. If a hush house is subject to New Source Review, then it is required to meet standards that prevent significant loss of visibility. In addition, many states have laws to prevent reduction of visibility. The standards are usually quantified in terms of opacity (degree of opaqueness) of the plume. Opacity at a source is visually measured according to the Ringelmann scale, which uses a series of charts to determine the opacity on a scale between 0 and 100%. The standards state that the plume opacity cannot exceed a given percentage. For example, in California, plume opacity can only exceed 20% for three minutes per hour. Note that the standards are established for opacity caused by solid particulates only and specifically exclude considering the effects of water in the determination of opacity.

Opacity of the exhaust plume during hush house operations is dependent on the type of engine being tested. Qualitative visual observations of plumes by Oak Ridge National Laboratory (ORNL) staff at several existing hush houses (e.g., Dobbins AFB and Otis AFB) indicate no problem for those engines. In fact, the plumes were very difficult to distinguish since they were virtually clear, except when an engine was operating in afterburner mode. Discussions with Air Force personnel indicate, however, that there exists a large variability in the opacity of plumes. For example, some engines have exceeded the opacity standard in California, which has required the Air Force to file a variance to allow testing of the engines. Regulatory agencies in California have agreed to the variance, but a provision has been included with the variance that the "dirtier" engines will be phased out over the next several years. Some of the engines will be retired from service and will be replaced with new "cleaner" engines, while others will be modified to burn "cleaner". Thus, the long-term plan is to replace or modify existing engines so that the opacity standard will be met without the need for a variance or pollution control equipment for the hush house.

Regarding a related issue, the exhaust plume should not induce fog formation, because of the large plume rise associated with the high exhaust temperatures and velocities. In summary, impacts associated with reduction of visibility are dependent on the type of engine involved.

3.3 Land Use Compatibility

Most of the information on land use compatibility guidelines for facilities on military installations is based on A-weighted noise criteria. As discussed in Sect. 1.2, hush houses satisfy acceptable A-weighted noise level criteria, but impacts resulting from non-audible, low-frequency, noise induced vibrations have raised concern. These vibrations have the potential for creating problems during the higher power settings associated with hush house operations. Vibrations may affect the structural elements of adjacent buildings and interfere with certain "sensitive" land uses, such as laboratories with sensitive equipment, administrative functions, and community/housing related functions. In addition, certain building types, such as pre-engineered metal or wood frame structures, seem to be more susceptible to vibrations. Many of the buildings in the flight line are constructed of these lightweight single solid panel or metal-skin materials with little sound absorption capability. Another key consideration is the orientation of adjacent buildings relative to the hush house axis; adjacent structures seem to be the most susceptible to adverse impacts if they are situated at an angle near the rear of the hush house structure (Fig. 2.2). Vibrations also seem to intensify in the upper stories of affected buildings.

At the present time the Air Force presumes that low-frequency (2-20 Hz) vibrations will be prevalent, but will not always be an apparent problem (U.S. Air Force, 1984b). Vibrations may be detectable up to 5000 ft with special equipment, a potential concern for sensitive land use functions at 3000 ft, and a possible problem within 1000 ft (U.S. Air Force, 1984b). Although the Air Force recognizes the need for hush house siting guidance, it is recognized however, that the use of performance standards based on local conditions is perhaps a preferable approach to hush house siting than the use of blanket criteria (U.S. Air Force, 1984c). In addition, site selection does not occur in a vacuum, as it should be in compliance with Base Comprehensive Planning (U.S. Air Force, 1984a) and U.S. Air Force, 1984a).

3.4 Survey Summary

In order to determine land use sensitivity to hush house operations and the corresponding implications for the siting of future hush houses, a telephone survey of environmental planners and civil engineers at bases with

operational hush houses is was conducted. The survey (Appendix C) focused on:

- (a) the types of land use functions adjacent to operational hush houses and their sensitivity to hush house operations.
- (b) the type of construction of adjacent buildings and their susceptibility to noise induced vibration,
- (c) potential air quality and plume capacity concerns associated with hush house emissions, and
- (d) any site-specific or general siting constraints that seemed relevant to the interviewee

The survey revealed that the types of land uses that are located adjacent (within 2000 feet) to operational hush houses are predominately related to aircraft operations and maintenance (e.g., jet engine shops, general purpose aircraft maintenance shelters, corrosion control facilities, avionics shops, and older test cells). Industrial land uses, such as warehouses, are also commonly located within a 2000 foot radius of operational hush houses. Administrative land uses adjacent to existing hush houses are most often related to wing/group headquarters or squadron operations. Housing, medical, and community land uses tend to be located away from the airfield taxiway and, on most bases, these land uses do not seem to be experiencing impacts from hush house operations. None of the base planners surveyed knew of any adverse impacts to offbase land uses from operational hush houses.

Of the bases surveyed (Appendix C) roughly onethird indicated that hush house operations were affecting on-site personnel in adjacent buildings. Many of the bases experiencing no adverse impacts from hush house operations have a hush houses sited in a remote area of the airfield taxiway that is free of sensitive receptors. Most of the impacts that do occur to adjacent land uses from hush house operations are within 1000 feet, with the exception of Langley AFB where concerns regarding building damage/window rattling from vibrations is occurring in base housing and community land uses up to 1000 feet from the hush house. Bases with congested land uses and/or with sensitive receptors, such as lightweight buildings situated at an angle near to the rear of the hush house, are the most prone to impacts. The issues

discussed below summarize the survey findings at bases with concerns regarding hush houses impact.

3.4.1 Building Damage

Some bases that are experiencing damage to adjacent buildings and their contents have attributed these problems to hush house operations. Vibrations are loosening the bolts in metal maintenance buildings 25 feet from the hush house at Hill AFB and 200 feet from the one at Dobbins AFB. Vibrations are thought to be causing cracks in a brick aircraft maintenance building 500 feet away from the hush house deflector at Dobbins AFB. The impact of vibrations on the glass surfaces of a brick aircraft maintenance building 400 feet from the hush house at Lambert AFB is generating concern. At Tyndall AFB vibrations during tests in afterburner mode have caused the vibration of light fixtures in a fuel shop 550 feet from the hush house and have necessitated the replacement of light bulbs. At Otis AFB², hush house induced vibrations rattle doors and windows in the crash fire station 700 feet across from the augmentor tube and rattle walls of a parachute drying room in the upper story of a shop 400 feet east of the hush house. At Langley AFB occupants in a brick family services building (500 ft from the hush house), a wooden chapel (1700 ft from the hush house), brick family housing facilities (1500-1800 ft from the hush house), and concrete temporary living facilities (700 ft from the hush house) have complained about window rattling. At the 50th Dakota ANG at Joe Foss Field, a wooden civil engineering building (400 feet and 45° NE of the hush house deflector) has undergone structural damage from hush house induced vibrations. The Arizona ANG at Fort Smith Municipal Airport also reports building damage and window rattling in metal structures with aircraft maintenance, industrial, and administrative functions. The land uses are all within 800 feet of the hush house. Finally, the Vermont ANG at Burlington International Airport has noticed a crack in the concrete foundation of a fuel maintenance hanger 100 feet from the hush house there is some uncertainty, however, as to whether the structural damage is due to hush house operations.

² Information regarding hush house operations at Otis AFB is based on a 1986 site visit by ORNL.

3.4.2 Interference with Sensitive Equipment

The use of sensitive equipment (e.g., in PMEL and avionics facilities) is often necessary for aircraft operations. The fact that vibrations from hush house operations are known to interfere with these sensitive functions has created siting problems for some bases. In some cases, these constraints have resulted in the siting of hush houses in remote areas of the airfield taxiway away from aircraft operations.

Hush house induced vibrations caused the interference with sensitive equipment at an avionics shop 150 ft from the hush house at Dobbins AFB and resulted in the relocation of the avionics shop. At Otis AFB it was reported that it is not possible to calibrate various instruments in a shop 400 feet east of the hush house during times when the hush house is in operation. Concrete block and brick avionics and PMEL facilities at Minot, McChord, McGuire, and MacDill are sited between 1000-2300 ft from existing hush houses with no apparent impact to sensitive equipment.

3.4.3 Long-Term Effects on Health from Vibrations

Personnel with administrative functions 400 feet from the hush houses at Dobbins and McConnell³ Air Force Bases expressed concern regarding long-term effects on their health from hush house induced vibrations. At the South Dakota ANG at Joe Foss Field, personnel in a wooden civil engineering building (see 3.4.1) are experiencing adverse health-related impacts from hush house operations. Some personnel in the building are adversely affected by a compression in their ears, which causes discomfort and difficulty in concentration. In addition the aircraft maintenance personnel in buildings 220-350 feet from the hush house at the Ohio ANG at Toledo Express Airport have expressed concerns regarding the long-term health effects from the vibrations.

3.4.4 Interference with Conversation

The administrative and aircraft maintenance personnel in buildings 200-500 feet from the hush house at Dobbins AFB indicated that hush house operations interfere with conversation. Hush house operations at the South

³ This observation regarding McConnell AFB is based on a 1986 site visit

Dakota ANG are also interfering with conversation in a wooden civil engineering building (see 3.4.3).

3.4.5 Noise/Startle Associated with the Afterburner Testing Mode

The greatest concern at a Dobbins AFB administrative building related to the noise/startle associated with the initiation of the after-burner testing mode. Personnel in a metal test cell building 400 feet from the hush house at Mountain Home AFB also had concerns regarding the noise associated with initiation of the afterburner testing mode.

3.4.6 Air Quality

Most of the bases that were surveyed claimed that the hush house plume emissions are low in visibility, appearing as heat or steam. Medium visibility (relative to base aircraft) was observed at Griffiss, Tyndall, and Dobbins Air Force Bases and at the ANG base at Hulman Field Regional Airport. Hush houses at both Tyndall AFB and Hulman Field, have heat and particulate emissions that are apparently very visible during afterburner mode. At Dobbins, emissions are visible from the highway 1000 ft north of the deflector. At McClellan AFB (California) the hush house did not pass the Ringelman opacity test, but the base obtained a variance for the hush house.

3.4.7 Long-Term Noise Abatement Performance

Long-term structural impacts to the hush house itself are potential concerns that were raised by planners at both Cannon AFB and the Indiana Air National Guard (ANG) base at Hulman Field Regional Airport. The hush house at Cannon AFB has been in operation since 1982 and some of the acoustical panels are coming loose. In addition, there are structural cracks in the concrete floor pad where the planes are anchored. The ANG hush house at Hulman Field has been in operation for four years. Although there have been no complaints from on personnel in adjacent buildings about vibrations or noise from the hush house, the maintenance personnel claim the noise associated with hush house operations is getting worse over time.

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4. MITIGATION

Vibrations induced by 10w-frequency acoustic emissions from hush houses may be reduced by the application of mitigation measures at either the receptor or the source (the hush house). Mitigation at the receptor may be accomplished by imposing siting constraints in combination with appropriate construction practices. Mitigation at the receptor is discussed in detail in Sect. 4.2.

4.1 Infrasound and Vibrations- Changing the Source

The information presented in Sects. 2.1 and 3.1 strongly suggest that the low frequency acoustic emission from hush houses originate from acoustic Cherenkov radiation produced by the near-field engine exhaust gas flow. Furthermore, the energy is coupled to the environment through a resonant mode of the augmenter (exhaust) tube. These findings indicate two possible approaches to the mitigation of vibrational impacts by means of hush house modification: suppression of the radiation at its source or alteration of the coupling mechanism. The latter measure could be achieved by changing the length of the augmenter tube. The spectral peak is sufficiently broad that it would be difficult to accomplish this by lengthening the tube since it is unlikely that a fixed elongated tube length could be found which would not support harmonics corresponding to any spectral component. Resonant modes could be eliminated by shortening the tube but this would cause increased thermal stress on the deflector and increase the overall noise level outside the facility.

Suppression at the source could be accomplished by direct intrusion in the exhaust flow, however, this would likely be unacceptable since it would impact engine performance by increasing the back pressure. A more promising approach is to eliminate, or reduce, the radiating portion of the exhaust plume by promoting the transition to turbulence. It is known that hydrodynamic instabilities can result by the superposition of flow fields. Thus, by creating a flow field which is known to destabilize a jet, a more rapid transition to a highly turbulent and, consequently, nonradiating flow structure would be achieved.

4.2 Siting as a Mitigative Measure

4.2.1 Vibrations

The low frequency acoustic waves emitted from operating houses can induce vibrations in other structures. Resulting impacts can include health effects, functional interference, and structural damage. These impacts can be minimized by the appropriate siting of hush houses or surrounding structures. It is currently not possible to rigorously establish siting guidelines for avoidance of vibrational impacts, however, some suggestions can be made on the basis of ISC and ANSI standards, the analysis of a model wall (Sect. 3.1.3) and the survey of bases with operational hush houses (Sect. 3.3).

Health Effects of Vibration- The criteria derived by the EPA (1982) using the ISO and ANSI Standards address three types of vibrational effects. These are: (1) whole body vibration of humans, (2) annoyance caused by building vibrations, and (3) structural damage from building vibrations. The first two will be addressed in this subsection, the third will be addressed below.

Knowledge is not complete in these areas and standards may be modified in the future. However, for the present application, an attempt has been made to suggest the most stringent requirements so that possible future tightening of standards would not adversely affect siting criteria.

The four physical factors of primary importance in determining the human response to vibration are: intensity, frequency, direction, and exposure time. Vibrational effects are only present during afterburner operation, which occurs 6 or 7 times per engine trim for a duration of 20s. Thus, exposure time is not considered to be an important variable in this analysis. In general, the standards have attempted to address these factors with regard to: (1) preservation of working efficiency, (2) preservation of health or safety, and (3) preservation of comfort.

Experience has shown that complaints of building vibrations are likely to arise from occupants if the vibration levels are only slightly in excess of perception levels. In general, the limits are related to acceptance by the occupants and are not determined by any other factors such as short-term health and work efficiency. Since the primary frequency is approximately 15 Hz, levels are based on the detection level of 10-39 for vibrations in the vertical plane (the most sensitive direction at 15 Hz). This level is then

adjusted by weighing factors according to ANSI (1983), for different building functions. These weighing factors allow greater vibrations for building uses which require less freedom from vibrations.

On the basis of the analysis of the model wall (Sect. 3.1.3) as well as guidance from ANSI (1983) and ISO (1974), distances from the hush house which are judged to be acceptable are presented in Table 4.1. It may be noticed

Table 4.1. Acceptable distances (in feet) from the hush house based on ANSI and ISO vibration recommendations.

Building Function	Weighting Factor	Percent window & door area in concrete/brick building						All	
		0	5	10	15	25	50	Steel Bldg	Wood Bldg
Hospital operating theatre and critical working areas	1	a	a	340	420	540	765	1080	765
Residence (night) (day)	1.4	a	a	a	300	385	545	770	545
	2	a	a	a	a	270	385	540	385
Office	4	a	a	a	a	a	a	270	a
Workshop	8	a	a	a	a	a	a	a	a

*Less than 250 ft.

that some of the acceptable distances to offices, residences, and shops for typical window plus door openings of 15-25% are small and less than distance for which some complaints have been received. One reason for this is that the model wall analysis does not consider building resonances. The most energetic portion of the hush house emission spectrum falls within the natural frequency range of building walls and other substructures (Sect. 3.1.3). In situations where building resonance occurs the model wall analysis is expected to significantly underpredict the level of vibration leading to acceptable distances which are too small. Another possible reason for this is that the levels in these functional situations are judged by ANSI, based on laboratory derived data, to be tolerant to 4

vibration sensitivity threshold but the actual occupants may not be tolerant. Where just the perception of vibrations is important the sensitivity threshold (weighing factor 1) is more appropriate.

Structural Impacts- In general, the potential for functional interference will diminish with distance from the hush house and with increasing mass density and rigidity of the building. Building size will also influence the potential for vibration-induced functional interference. Buildings with walls which have large areas exposed to incident acoustic waves are expected to be more prone to functional interference. Vibration-induced accelerations no greater than 10⁻⁴ g are necessary to ensure that no interference with vibration-sensitive functions will occur. In order to minimize the potential for vibration-induced functional interference, it is recommended that:

- (1) no vibration sensitive functions (PMEL, avionics) be located within 500 ft of a hush house,
- (2) vibration sensitive functions be restricted to small, single story concrete block building, between 500 ft and 1000 ft of a hush house,
- (3) single story, pre-engineered steel buildings should be located no closer than 1000 ft from a hush house, and
- (4) multi-story, pre-engineered steel buildings used for vibration sensitive functions should be sited at least 2000 ft from a hush house.

Siting constraints based upon structural damage should only be slightly less restrictive than those for functional interference. It is recommended that the siting constraints described for functional interference be satisfied with the exception that single story pre-engineered structures be excluded within 500 ft of the hush house, rather than 1000 ft.

4.2.2 Audible Sound

The acceptance criteria of noise levels not exceeding 89 dB(A) anywhere beyond a 250 ft radius of a T-10 hush house should be sufficient to alleviate any health concerns relative to audible noise (Table 4.2). The limited experience with the T-9 suggests that this radius should be somewhat greater, about 350 ft, for this type of noise suppressor. As mentioned under

Table 4.2. Exclusion distances based on human effects for maximum sound pressure levels.

Source/Health Effect	Target Noise Level (Outside)	Exclusion Distance* (ft)
Infrasound (15 Hz)		
Chronic	95 dB	4000 Assuming building attenuation
Acute	120 dB	250 "
Noise (A-weighted)		
Hearing Loss	89 dBA 100 dBA	250 open work area 2000 building (assuming 15 dB attenuation)
Speech Interference	80 dBA (assume 15 dB 65 dBA	800 95% indoor sentence intelligibility 4000 95% outdoor sentence intelligibility at 2 meters raised voice

*Directly behind augmentor tube.

vibration (Sect. 4.2.1), afterburner power is achieved in 6 or 7 bursts of approximately 20s each per engine trim. This means that the duration of exceedance is small and should not result in adverse health consequences although annoyance could occur. If the performance of audible noise suppression is maintained during the life of the hush house, there appears to be no health reason to be more restrictive. Mitigation of health impacts is thus accomplished via maintenance of acceptance criteria and utilization of the compliance zone. Other concerns relate to speech interference and general annoyance. The approximate distances to mitigate these effects are presented in Table 4.2.

4.2.3 Zones of Influence

The zones of influence listed in Table 4.3 represent minimum separation distances for mitigating hush house noise and vibrational impacts on

adjacent buildings and functions. These guidelines for minimum distances integrate information to date regarding the compatibility of land use functions and construction types with hush house operations. These zones of influence are based upon a worst case comparison of the analyses and survey of base complaints described in Sect. 3, as well as interim siting guidance (U.S. Air Force, 1984b) and are not meant to serve as blanket criteria. Since each base has unique operational and land use constraints, these zones of influence can serve as input into the overall base comprehensive planning process.

Table 4.3. Zones of influence.

Building Function	Distance (ft)*
Workshop (full-time occupancy) masonry with 15-25% door and window openings**	500
Pre-fabricated steel buildings single story	500
Office - masonry with 15-25% door and window openings**	
single story	500
multi-story	1000
Vibration sensitive equipment (e.g., optical microscopes, photo interpretation light tables)	
single story/ concrete block	500-1000
single story pre-fabricated steel	1000
multi-story pre-fabricated steel	2000
Residential/Community***	
community	1000-3000
housing	2000
medical	3000

* Radial distance as measured from both ends of exhaust tube

** Using Table 4.1 weighing factor of 1.

*** HQ AFLC DEPV, Interim Site Planning Guidance for Aircraft Jet Engine Hush House Facilities,. July 10, 1984.

Since all distances given above are greater than 250 ft, these recommendations ensure that significant audible noise impacts will not occur.

Air quality impacts are expected to be significant only in locations where the ambient air quality is quite poor. In these situations, ground level pollutant concentrations could be near maximum values over distances in excess of 1 mile. Since exceedances of air quality standards are expected to be both rare and site specific, it is inappropriate to define zones of influence based upon this issue.

4.3 Air Quality

Air quality impacts have been evaluated for two issues: concentrations of pollutants in the ambient air and reduction of visibility caused by the exhaust plume. The need for mitigation is dependent on the type of engine being tested, frequency of testing, location of the hush house, and applicable air quality standards.

Engine emissions during hush house operations do not significantly affect the ambient air. Therefore mitigation is unnecessary unless the frequency and duration of testing are great enough for emissions to exceed the level which requires review by governing regulatory agencies. This latter scenario, which would be most likely for nitrogen dioxide, can be somewhat mitigated by siting the hush house as far as possible from the nearest fence line and by orienting the exhaust tube to direct pollutants away from the nearest fence line. Careful siting provides only limited benefits, however, because concentrations that are almost as large as the maximum concentration occur at distances which are beyond the fence line for varying meteorological conditions. Control technology is also available to mitigate impacts, but at significant cost.

Mitigation measures to improve visibility include the replacement of existing "dirty" engines with new "cleaner" engines, the modification of existing engines to burn "cleaner", and the use of controls such as wet scrubbers that may reduce the exhaust plume opacity, but at substantial cost. A wet scrubber, resembling a waterfall in the exhaust tube, would mask the smoke by creation of a moisture-laden plume. Opacity would be measured downwind of the "moisture plume's" evaporation because opacity standards are for plume opacity caused by solid particulates only and specifically exclude considering the effects of water. Thus, not only would the wet scrubber remove a portion of the smoke's particulates which are reducing visibility, but measurement of opacity downwind of the "moisture plume" would allow time

for the smoke to diffuse in the atmosphere. A disadvantage of wet scrubbers is that they may exert enough "back pressure" to alter the performance characteristics of the engine being tested. Fuel additives are another means to mitigate reduced visibility. Fuel additives would reduce the amount of smoke in the exhaust plume, but may also alter engine performance.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

This report investigates the potential impacts of hush house operations. Specific issues considered include: air quality; the health effects of noise, infrasound and vibration; interference with adjacent functions, and structural damage in nearby buildings associated with hush house induced vibrations. Since the magnitude of potential impacts will depend upon land uses and their distance from the hush house, impacts are considered on the basis of current and anticipated land use patterns.

It is found that audible noise and air quality impacts of hush house operations are not significant. The 89 dbA performance criterion at 250 ft from the hush house is sufficient to ensure that there are no chronic or acute effects on hearing. However, it has been suggested by some surveyed personnel that the noise abatement performance of older hush houses has diminished with time. This may be caused by deterioration of the acoustic panels as the result of exposure to the wind and rain, changes in hush house operations, or hush house modification such as the removal of acoustic panels to admit more ambient air. This concern can be addressed by performing noise surveys at several hush houses where this concern has been raised.

Issues associated with air quality are concentrations of air pollutants and plume visibility. It is expected that hush houses will comply with air quality standards, except in areas where the ambient air quality is quite poor. In these areas, it may be necessary to site hush houses several miles from either base boundaries or base housing. Plume visibility is a function of the engine being tested. In several cases plume visibility has been excessive; however, the opacity of the plume could be reduced by appropriate fuel additives. .

The most significant impacts identified in this study are the physical and physiological effects associated with the low-frequency acoustic (infrasound) emissions from hush houses. Annoyance can occur either as a result of direct exposure to infrasound or exposure to structural vibrations induced by the infrasound. The accuracy of estimates of human annoyance has yet to be determined. Results of the surveys conducted by ORNL staff could be used as a guide to determine if the type of personnel employed and their concerns and sensitivities to vibration are in line with recommended standards. Uncertainty in these estimates may be large; however, at present the only current recommendations are provided by ANSI/ISO documents and these

are mostly derived from laboratory-based studies of comfort, performance and fatigue.

Actual infrasound measurements at the source and at nearby work areas would be a significant step towards reducing these uncertainties. These measurements should be conducted periodically as the buildings age to provide accurate data for assessment. If possible, measurements to determine if the older hush houses have changed in their performance characteristics might provide a quicker resolution of the problem.

Base land use plans could be structured so that the more durable, vibration insensitive buildings would be located closer to the hush houses. They would absorb and deflect infrasound, thus providing some protection to other structures in their shadow.

Impacts of infrasound induced structural vibrations include structural integrity and interference with vibration sensitive functions, such as avionics labs and PMEL's. Two approaches for mitigation of these impacts have been identified. These are hush house modification to reduce the magnitude of low frequency acoustic emissions or siting requirements which would limit land uses and construction types in the vicinity of operating hush houses. Siting constraints may ultimately be required; however, this approach to mitigation is undesirable for two reasons. First, such constraints would conflict with effective land use planning around hush houses and present severe constraints at installations with limited land availability. Second, the development of siting criteria would require both a better understanding of human response to vibration and comprehensive vibroacoustic field studies. Consequently, the cost and time requirements associated with the development of reliable siting criteria would be excessive.

It is likely that the development and implementation of mitigation measures applied at the source could be accomplished more quickly and at a lesser cost. If such mitigation is completely successful only minimal siting constraints would be required. A moderate reduction in infrasonic emissions could still require the development of siting constraints but these would be less restrictive and the studies required for their development would be more focused.

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APPENDIX A: PROPAGATION OF SOUND THROUGH A BARRIER

As a model for studying the propagation of sound through the walls of a structure, let us consider the wall thickness to be small compared to the wavelength of the incident sound, the wall to have structural stiffness, mass, and be elastically supported (as if on an elastic foundation). First the relevant equations for sound propagation on both sides of the wall will be studied and then the matching conditions at the wall will be derived. Finally the transmitted sound wave will be obtained as a function of the incident sound wave.

For a "perfect" gas with zero mean velocity and uniform, average state properties, the relevant equations for a small linear disturbance are

Continuity

$$\frac{\partial \rho}{\partial t} + \bar{\rho} v_{k,k} = 0 \quad (1)$$

Momentum

$$\bar{\rho} \frac{dv_i}{dt} + p_{,i} = 0 \quad (2)$$

where $\bar{\rho}$ = average density

ρ = density perturbation

v_i = velocity perturbation

p = pressure perturbation.

Because a sound disturbance in a gas occurs with the gas at almost isentropic conditions,

$$p = p(\rho) ; \quad p_{,i} = \frac{dp}{d\rho} \rho_{,i} = a^2 \rho_{,i}$$

where a = velocity of sound.

The momentum equation may therefore be written

$$-\rho \frac{\partial v_i}{\partial t} + a^2 \rho_{,i} = 0 . \quad (3)$$

Eliminating ρ between momentum and continuity yields

$$\frac{\partial^2 v_i}{\partial t^2} - a^2 v_{k,ki} = 0 . \quad (4)$$

If an exponential wave solution of the form

$$v_i = \hat{v}_i \exp i (\alpha_k x_k - \beta t)$$

is sought, the dispersion relation relating the wave number vector α_i and the wave frequency β

$$\beta^4 - a^2 (\alpha_1^2 + \alpha_2^2) \beta^2 = 0 \quad (5)$$

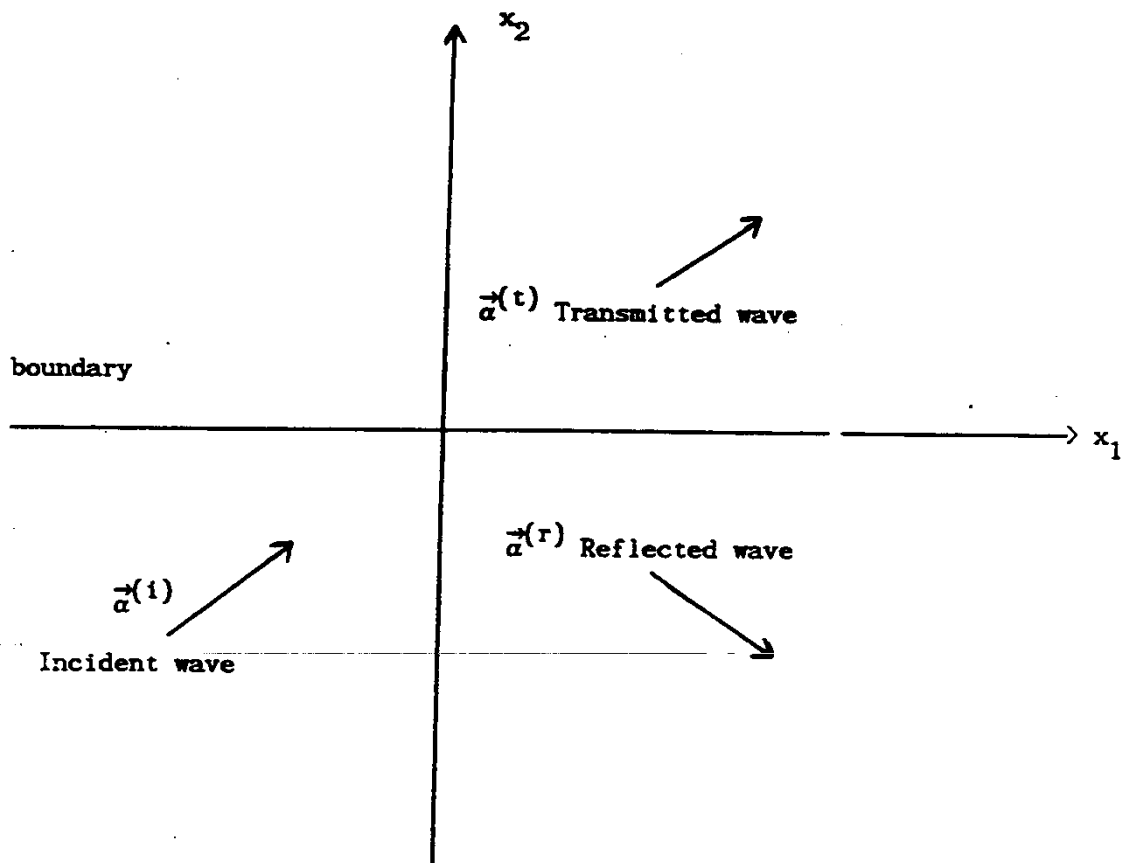
is obtained for a wave in x_1, x_2 space with v_1 having no component in the x_3 direction.

The dispersion relation is seen to have two solutions corresponding to two wave modes:

$$\beta^2 = 0 \quad \text{degenerate shear wave (zero viscosity) and} \quad (6)$$

$$\beta^2 = a^2 (\alpha_1^2 + \alpha_2^2) \quad \text{dilatational wave.} \quad (7)$$

The situation of incident, reflected and transmitted waves at a boundary may be pictured as shown below.



If a thin, flexible barrier with mass exists along the x_1 coordinate axis ($x_2 = 0$) with air on each side, the matching conditions of the gas to the barrier on each side are that the net normal force of the gas acts on the barrier and that the normal components of the velocities of the gas on both sides are the same as the normal velocity of the barrier.

Consider $x_2 < 0$ as side (1) and $x_2 > 0$ as side (2). Therefore $v_2^{(1)}(x_2 = 0) = v_2^{(2)}(x_2 = 0) = v_x(\text{barrier})$ and $\alpha_1^{(1)} = \alpha_1^{(2)}$.

In general, there will be a transmitted wave on side (2) and a reflected wave on side (1) for an incident wave on side (1). Therefore

$$\alpha_1^{(i)} = \alpha_1^{(r)} = \alpha_1^{(t)}$$

For the case of the gas on both sides of the barrier having the same average temperature

$$\alpha_2^{(i)} = \alpha_2^{(t)} = -\alpha_2^{(r)}$$

where the superscripts i, t, r, refer to incident, transmitted and reflected respectively. Also, at the boundary

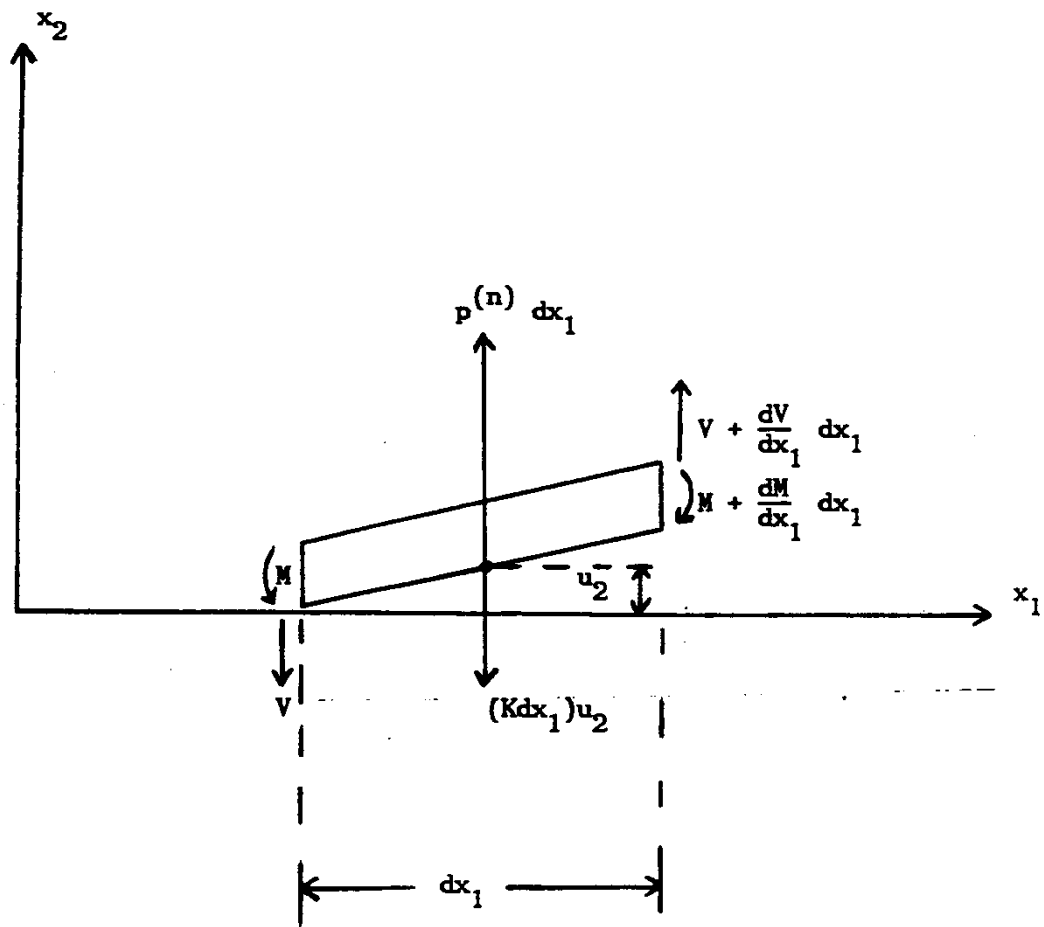
$$v_2^{(i)} + v_2^{(r)} = v_2^{(t)} = v_2^{(b)}$$

where $v_2^{(b)}$ is the velocity of the boundary in the x_2 direction.

The loading on the barrier $p^{(n)}$ is given by

$$p^{(n)} = p^{(i)} + p^{(r)} - p^{(t)}$$

The dynamics of the barrier will now be examined.



If M is the bending moment and V is the shear on the barrier (per unit thickness in the x_3 direction), then to first order in dx_1

$$Vdx_1 - \frac{dM}{dx_1} dx_1 = 0 \quad (8)$$

$$\text{or } V = \frac{dM}{dx_1} .$$

Also, if the elastic stiffness of the barrier (per unit thickness in the x_3 direction, is denoted as S , then

$$M = S \frac{\partial^2 u_2}{\partial x_1^2} . \quad (9)$$

Therefore, the force equilibrium equation for the barrier is given by

$$p^{(n)} - m \frac{\partial^2 u_2}{\partial t^2} + S \frac{\partial^4 u_2}{\partial x_1^4} - Ku_2 = 0 \quad (10)$$

where m is the mass of the barrier and K is the elastic support constant of the barrier per unit barrier area, respectively.

From eq (4) and the form of $v_1 = \hat{v}_1 \exp i(\alpha_k x_k - \beta t)$

$$\frac{\hat{v}_2}{\hat{v}_1} = \frac{\beta^2 - a^2 \alpha_1^2}{a^2 \alpha_1 \alpha_2} = \frac{\alpha_2}{\alpha_1} . \quad (11)$$

From eq (2), the pressure perturbation is given by

$$\hat{p} = \frac{\beta}{\alpha_2} \bar{\rho} \hat{v}_2 \quad (12)$$

and

$$\frac{\hat{v}_2(i)}{\hat{v}(i)} = \frac{\hat{v}_2(t)}{\hat{v}_1(t)} = - \frac{\hat{v}_2(r)}{\hat{v}_1(r)} \quad (13)$$

From eq (10) after differentiation with respect to t and substitution of $\hat{v}_2(t) = \frac{\partial u_2}{\partial t}$, it follows

$$-i \beta \hat{p}^{(n)} + \beta^2 m \hat{v}_2^{(t)} + \alpha_1^4 S \hat{v}_2^{(t)} - K \hat{v}_2^{(t)} = 0 \quad (14)$$

$$\text{or } i \beta \hat{p}^{(n)} = (\beta^2 m + \alpha_1^4 S - K) \hat{v}_2^{(t)} \quad (15)$$

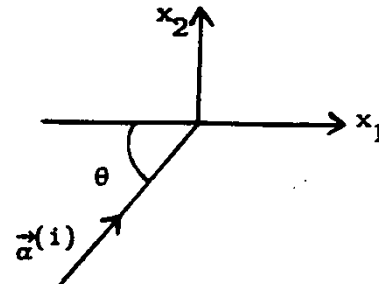
$$\text{Since } \hat{p}^{(n)} = \hat{p}^{(i)} + \hat{p}^{(r)} - \hat{p}^{(t)} = \frac{\beta}{\alpha_2(i)} \bar{\rho} (\hat{v}_2^{(i)} - \hat{v}_2^{(r)} - \hat{v}_2^{(t)}), \quad (16)$$

$$\text{then } (\beta^2 m + \alpha_1^4 S - K) \hat{v}_2^{(t)} = \frac{2i\beta^2}{\alpha_2(i)} \bar{\rho} (\hat{v}_2^{(i)} - \hat{v}_2^{(t)}) \quad (17)$$

and the ratio of $\frac{\hat{v}_2^{(t)}}{\hat{v}_2^{(i)}}$ may be easily obtained.

For the case $S = K = 0$ (no elastic stiffness and support)

$$\frac{\hat{v}_2(t)}{\hat{v}_2(i)} = \frac{1}{1 - \frac{ia_2(i)}{2} \frac{m}{\rho}}$$



Letting $\alpha_2^{(i)} = |\alpha| \sin(\theta)$

and $|\alpha| = \frac{\beta}{a}$

$$\frac{\hat{v}_2(t)}{\hat{v}_2(i)} = \frac{1}{1 - \frac{1}{2} \frac{\beta}{a} \frac{m}{\rho} \sin(\theta)} \quad (18)$$

Therefore for a normally incident wave, $\theta = 90$ and

$$\frac{\hat{v}_2(t)}{\hat{v}_2(i)} = \frac{1}{1 - \frac{1}{2} \frac{\beta}{a} \frac{m}{\rho}} \quad (19)$$

To minimize $\left| \frac{\hat{v}_2(t)}{\hat{v}_2(i)} \right|$, one must maximize $\frac{m}{\rho}$.

This can be done by building a double wall of say sheet metal and filling the space with say sand.

APPENDIX B: DERIVATION OF WALL ACCELERATIONS

Let P be the acoustic wave overpressure at a distance r_o from the source (hush house) and let \bar{P} be the associated pressure level in db.

$$\bar{P} = 20 \log_{10} (P/P_o) \quad (1)$$

where $P_o = 0.0002 \mu \text{ bar}$ ($1 \mu \text{ bar} = 14.7 \times 10^{-6} \text{ psi}$). From Eq. (1)

$$P = P_o 10^{(\bar{P}/20)} \quad (2)$$

Assuming that the pressure wave is spherical, the pressure at a distance r from the source can be deduced from a known pressure level \bar{P} at r_o by

$$P(r) = \frac{r_o}{r} P_o 10^{(\bar{P}/20)} \quad (3)$$

Conservation of mass relates pressure to velocity

$$\rho \frac{\partial v_r}{\partial t} = - \frac{\partial P}{\partial r} \quad (4)$$

where ρ is the density of air and v_r is the radial velocity component. It is assumed that distance r is sufficiently far from the source that the acoustic wave front is planar so that

$$v_r = \bar{v} e^{i(\alpha r - \omega t)} \quad (5)$$

and

$$P = P' e^{i(\alpha r - \omega t)} \quad (6)$$

where P' and \bar{v} are the pressure and velocity amplitudes, respectively, α is the radial component of the wavenumber vector and ω is the angular frequency. Substituting Eqs. (5) and (6) into Eq. (4) yields

$$\bar{v} = P' / \rho c \quad (7)$$

where $c = \omega / \alpha$ is the speed of sound. Using Eq. (7) in Eq. (3) provides the relationship between the amplitude of the radial velocity at an arbitrary distance r from the source and the known pressure level \bar{P} at distance r_0

$$\bar{v}(r) = \frac{r_0}{r} \frac{P_0}{\rho c} 10^{(\bar{P}/20)} \quad (8)$$

From Appendix A, the ratio of the induce wall velocity to the incident velocity normal to the plane of the wall is

$$F = v_{\text{wall}} / v_2^{(i)} = 2i\beta^2 \rho / \left[\alpha_2^{(i)} \left[\beta_m^2 + \alpha_1^4 S - k + \frac{2i\beta^2 \rho}{\alpha_2^{(i)}} \right] \right] \quad (9)$$

where $\alpha_2^{(i)} = \alpha \sin(\theta)$, $\alpha_1 = \alpha \cos(\theta)$, and θ is the angle between the plane of the wall and the direction of propagation of the incident wave. For a wave which is incident normal to the wall, $\theta = 90^\circ$. Neglecting wall

stiffness and spring constant ($S = k = 0$). Eq. (9) becomes

$$v_{\text{wall}}/v_2^{(i)} = 2i\beta^2\rho/\left[\alpha_2^{(i)}\beta_m^2 + 2i\beta^2\rho\right] = F. \quad (10)$$

Equation (10) is complex which implies that the induced wall wave undergoes both a change in amplitude and a phase shift with respect to the incident wave. Since for the purposes of this study the phase shift is of no concern, Eq. (10) is written in the form

$$F = R e^{i\phi}, \quad (11)$$

where

$$R = 2\rho/[\bar{m}^2\alpha^2\sin^2(\theta) + 4\rho^2]^{1/2}. \quad (12)$$

is the wall amplification (or damping) factor. Substituting Eq. (12) into Eq. (10) yields

$$v_{\text{wall}} = \left[2\rho/(\bar{m}^2\alpha^2\sin^2(\theta) + 4\rho^2)^{1/2}\right] v_2^{(i)}. \quad (13)$$

The incident velocity component normal to the plane of the wall $v_2^{(i)} = \bar{V}(r) \sin(\theta)$ so that

$$v_{\text{wall}} = R \bar{V}(r) \sin(\theta). \quad (14)$$

The wall acceleration $A_{\text{wall}} = \left| \frac{\partial v}{\partial t} \right|_{\text{wall}}$ and from Eqs. (5) and (14)

$$A_{\text{wall}}(r) = \omega R \bar{V}(r) \sin(\theta) . \quad (15)$$

Substituting Eqs. (8) and (13) into Eq. (15) yields

$$A_{\text{wall}}(r) = \{2\omega r_0 P_0 \sin(\theta) / [rc(m^2 \alpha^2 \sin^2(\theta) + 4\rho^2)^{1/2}]\} 10^{(\bar{P}/20)} . \quad (20)$$

which relates the wall acceleration at a distance r from the source (hush house) to the pressure level \bar{P} which is known at a distance r_0 from the source.

From Eq. (20), the distance \bar{r} at which the wall acceleration will be less than or equal to \bar{a} is

$$\bar{r} = \{2\omega r_0 P_0 \sin(\theta) / [\bar{a}c(m^2 \alpha^2 \sin^2(\theta) + 4\rho^2)^{1/2}]\} 10^{(\bar{P}/20)} . \quad (21)$$

In the analysis presented in this report, $\bar{P} = 110$ db at $r_0 = 250$ ft. and at the circular frequency $f = \omega/2\pi = 15$ Hz, $C = 1100$ fps, $\alpha = \omega/c$, and $m = 45$ lbs/ft² for concrete block walls $m = 2$ lbs/ft² for wood frame walls, and $m = 1$ lb/ft² for pre-engineered steel panelled walls.

APPENDIX C: THE ORNL SURVEY

Hush House Protocol

Name of Base: _____

Name of planner/civil engineer: _____

Phone Number: _____

Date: _____

Questions

1. Hello. This is _____ with Oak Ridge National Laboratory. Have you had time to read the letter and survey you received regarding an Environmental Study for the U.S. Air Force on the impacts of Hush Houses on Base residents and operations?

☐ Yes

☐ No*

*Give information speech

Unless you have any questions, we can proceed with the interview.

2. Are there one or more operational Hush Houses at your base?

☐ Yes

☐ No*

*Give termination speech

How many?

☐ One

☐ Two

☐ Three

3. How long has it (each) been operating?

#1

#2

#3

☐ ☐ ☐ 1 year or less

☐ ☐ ☐ 2-4 years

☐ ☐ ☐ 5-7 years

4. How frequently is it (each) used?

<u>#1</u>	<u>#2</u>	<u>#3</u>	
[]	[]	[]	Three or more time daily
[]	[]	[]	Once or twice dally
[]	[]	[]	Every other day
[]	[]	[]	Twice a week
[]	[]	[]	Once a week
[]	[]	[]	Varies (please specify for each Hush House):
			#1 _____
			#2 _____
			#3 _____

5. What type of aircraft have been used in the Hush Houses(s)?

<u>#1</u>	<u>#2</u>	<u>#3</u>	
[]	[]	[]	F15
[]	[]	[]	F16
[]	[]	[]	F111
[]	[]	[]	F4
[]	[]	[]	F105
[]	[]	[]	F106
[]	[]	[]	F5
[]	[]	[]	A7
[]	[]	[]	other (please identify for each Hush House):
			#1 _____
			#2 _____
			#3 _____

6. What type of engines have been tested in the Hush Houses(s)?

<u>#1</u>	<u>#2</u>	<u>#3</u>	
[]	[]	[]	F100PN100/200
[]	[]	[]	TF30-/9/11/100
[]	[]	[]	J79-15/17
[]	[]	[]	J75-17/19
[]	[]	[]	J85-5/21
[]	[]	[]	TF34G3100
[]	[]	[]	TF41-A-1A/B
[]	[]	[]	other (please identify for each Hush House):
			#1 _____
			#2 _____
			#3 _____

7. What are the on-site land uses adjacent to the Hush House?

		<u>#1</u>	<u>#2</u>	<u>#3</u>
<u>Aircraft Maintenance:</u>	Test Call	[]	[]	[]
	Hush House	[]	[]	[]
	Gen Purp	[]	[]	[]
	Jet Engine Shop	[]	[]	[]
	Corrosion Control	[]	[]	[]
	Avionics Shop	[]	[]	[]
<u>Industrial:</u>	Warehouses	[]	[]	[]
	Petroleum Op	[]	[]	[]
	Hydrant Fueling	[]	[]	[]
	POL Op Storage	[]	[]	[]
	Explosive Storage	[]	[]	[]
	Hazardous Storage	[]	[]	[]
	PMEL	[]	[]	[]
<u>Administrative:</u>	Wing/Group HQ	[]	[]	[]
	CBPO	[]	[]	[]
	Civilian Personnel	[]	[]	[]
	Family Services	[]	[]	[]
	Data Processing	[]	[]	[]
<u>Community:</u>	Commissary Stores	[]	[]	[]
	Exchange Sales	[]	[]	[]
	Bank/Credit Union	[]	[]	[]
	Central Post Office	[]	[]	[]
	Schools	[]	[]	[]
	Chapels	[]	[]	[]
	Museum	[]	[]	[]
	Library	[]	[]	[]
<u>Medical:</u>	Hospital	[]	[]	[]
	Dental Clinic	[]	[]	[]
<u>Housing:</u>	Family Housing	[]	[]	[]
	TLF	[]	[]	[]
	BOQ	[]	[]	[]
	UEPH	[]	[]	[]
	VOQ	[]	[]	[]
	VAQ	[]	[]	[]

Other (please specify for each Hush House):

#1 _____

#2 _____

#3 _____

8. How far are these buildings from the Hush House? [give distance (feet) and compass position (degrees from north) from the Hush House, and the size (square feet) of each land use]

	<u>Building</u>	<u>Distance</u>	<u>Orientation</u>	<u>Size</u>
#1				
#2				
#3				

9. Of what construction types are these adjacent buildings?

Hush House #1:

<u>Each House W/:</u>		Concrete	Metal	Brick	Wood	Other	(specify)
<u>Aircraft Maintenance:</u>							
	Test Cell	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
	Hush House	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Gen Purp		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
	Jet Engine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
	Corrosion Control	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
	Avionics	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

Industrial

Warehouses	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Petroleum Op	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Hydrant Fueling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
POL OP Stor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Explosive Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Hazardous Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
PMEL	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

Hush House #2 (cont):

	Concrete	Metal	Brick	Wood	Other	(specify)
--	----------	-------	-------	------	-------	-----------

Aircraft Maintenance:

	Test Cell	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Hush House	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	Gen
Purp	[]	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Jet Engine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Corrosion Control	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Avionics	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	

Industrial:

	Warehouses	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Petroleum Op	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Hydrant Fueling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	POL OP Stor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Explosive Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Hazardous Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	PMEL	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	

Administrative:

	Wing/Group HQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	CBPO	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Civilian Personnel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Family Services	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Data Proc	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	

Community:

	Stores	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Exchange Sales	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Bank/Credit Union	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Post Office	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Schools	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Chapel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Museum	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	
	Library	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____	

Hush House #2 (cont):

	Concrete	Metal	Brick	Wood	Other (specify)
--	----------	-------	-------	------	-----------------

Medical:

Hospital	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Dental Clinic	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Gen Purp	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____

Housing:

Family Housing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
TLF	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
BOQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
UEPH	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
VOQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
VAQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____

Hush House #3:Aircraft Maintenance:

Test Cell	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Hush House	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Gen Purp	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Jet Engine	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Corrosion Control	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Avionics	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____

Industrial:

Warehouses	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Petroleum Op	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Hydrant Fueling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
POL OP Stor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Explosive Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
Hazardous Storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____
PMEL	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> _____

Hush House #3 (cont):

Concrete Metal Brick Wood Other (specify)

Administrative:

Wing/Group HQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
CBPO	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Gen Purp	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Civilian Personnel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Family Services	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Data Proc	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

Community:

Stores	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Exchange Sales	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Bank/Credit Union	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Post Office	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Schools	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Chapel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Museum	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Library						

Medical:

Hospital	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Dental Clinic	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

Housing:

Family Housing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
TLF	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
BOQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
UEPH	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
VOQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
VAQ	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

10. How many stories do the adjacent buildings have?

	#1					#2					#3				
	1	2	3	4	+	1	2	3	4	+	1	2	3	4	+
<u>Aircraft Maintenance:</u>															
Test Call	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]
Hush House	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]
Gen Purp	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]
Jet Engine Shop	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]
Corrosion Control	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]
Avionics Shop	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]	[]

Industrial:

Warehouses	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Petroleum Op	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Hydrant Fueling	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
POL Op Storage	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Explosive Storage	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Hazardous Storage	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
PMEL	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []

Administrative:

Wing/Group HQ	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
CBPO	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Civilian Personnel	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Family Services	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Data Processing	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []

Community:

Commissary Stores	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Exchange Sales	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Bank/Credit Union	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Central Post Office	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Schools	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Chapels	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Museum	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []
Library	[] [] [] [] [] []	[] [] [] [] [] []	[] [] [] [] [] []

Medical:

Hospital	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dental Clinic	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

	<u>#1</u>	<u>#2</u>	<u>#3</u>
	1 2 3 4+	1 2 3 4+	1 2 3 4+
<u>Housing:</u>			
Family Housing	[] [] [] []	[] [] [] []	[] [] [] []
TLF	[] [] [] []	[] [] [] []	[] [] [] []
BOQ	[] [] [] []	[] [] [] []	[] [] [] []
UEPH	[] [] [] []	[] [] [] []	[] [] [] []
VOQ	[] [] [] []	[] [] [] []	[] [] [] []
VAQ	[] [] [] []	[] [] [] []	[] [] [] []

11. Has there been any response from on-site personnel in adjacent buildings about vibration or noises from the Hush House(s)?

[] Yes

[] No*

*Go to question 13

If so, which on-site bulidings/land uses have been affected?

	<u>#1</u>	<u>#2</u>	<u>#3</u>
<u>Aircraft Maintenance:</u>			
Test Call	[]	[]	[]
Hush House	[]	[]	[]
Gen Purp	[]	[]	[]
Jet Engine Shop	[]	[]	[]
Corrosion Control	[]	[]	[]
Avionics Shop	[]	[]	[]
<u>Industrial:</u>			
Warehouses	[]	[]	[]
Petroleum Op	[]	[]	[]
Hydrant Fueling	[]	[]	[]
POL Op Storage	[]	[]	[]
Explosive Storage	[]	[]	[]
Hazardous Storage	[]	[]	[]
PMEL	[]	[]	[]
<u>Administrative:</u>			
Wing/Group HQ	[]	[]	[]
CBPO	[]	[]	[]
Civilian Personnel	[]	[]	[]
Family Services	[]	[]	[]
Data Processing	[]	[]	[]

		#1	#2	#3
<u>Community:</u>	Commissary Stores	[]	[]	[]
	Exchange Sales	[]	[]	[]
	Bank/Credit Union	[]	[]	[]
	Central Post Office	[]	[]	[]
	Schools	[]	[]	[]
	Chapels	[]	[]	[]
	Museum	[]	[]	[]
	Library	[]	[]	[]
<u>Medical:</u>	Hospital	[]	[]	[]
	Dental Clinic	[]	[]	[]
<u>Housing:</u>	Family Housing	[]	[]	[]
	TLF	[]	[]	[]
	BOQ	[]	[]	[]
	UEPH	[]	[]	[]
	VOQ	[]	[]	[]
	VAQ	[]	[]	[]

Other (please specify for each Hush House): #1 _____
 #2 _____
 #3 _____

12. Were any of the following concerns voiced? (record on matrix below)
- Fear of damage to the buildings or its contents (window rattling, building shaking?)
 - Interference with the use of sensitive equipment?
 - Interference with conversation or other activities?
 - Long-term effects on health from subsonic vibrations?
 - Concerns regarding noise associated with initiation of the after-burner testing mode.
 - Other.

Hush House #1

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
<u>Aircraft Maintenance:</u>					
Test Cell	[]	[]	[]	[]	[]
Hush House	[]	[]	[]	[]	[]
Gen Purp	[]	[]	[]	[]	[]
Jet Engine	[]	[]	[]	[]	[]
Corrosion Control	[]	[]	[]	[]	[]
Avionics	[]	[]	[]	[]	[]
	[] Other _____				
	(specify) _____				
	f _____				

Hush House #1 (contd):

Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
----------------------	----------------------	------------------------	----------------------	------------------------

Industrial:

Warehouses	[]	[]	[]	[]	[]
Petroleum Op	[]	[]	[]	[]	[]
Hydrant Fueling	[]	[]	[]	[]	[]
POL OP Stor	[]	[]	[]	[]	[]
Explosive Storage	[]	[]	[]	[]	[]
Hazardous Storage	[]	[]	[]	[]	[]
PMEL	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Administrative:

Wing/Group HQ	[]	[]	[]	[]	[]
CBPO	[]	[]	[]	[]	[]
Civilian Personnel	[]	[]	[]	[]	[]
Family Services	[]	[]	[]	[]	[]
Data Proc	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Community:

Stores	[]	[]	[]	[]	[]
Exchange Sales	[]	[]	[]	[]	[]
Bank/Credit Union	[]	[]	[]	[]	[]
Post Office	[]	[]	[]	[]	[]
Schools	[]	[]	[]	[]	[]
Chapel	[]	[]	[]	[]	[]
Museum	[]	[]	[]	[]	[]
Library	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Hush House #1 (contd):

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
Medical:					
Hospital	[]	[]	[]	[]	[]
Dental Clinic	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

Housing:

Family Housing	[]	[]	[]	[]	[]
TLF	[]	[]	[]	[]	[]
BOQ	[]	[]	[]	[]	[]
UEPH	[]	[]	[]	[]	[]
VoQ	[]	[]	[]	[]	[]
VAQ	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

Hush House #2:

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
Aircraft Maintenance:					
Test Cell	[]	[]	[]	[]	[]
Hush House	[]	[]	[]	[]	[]
Gen Purp	[]	[]	[]	[]	[]
Jet Engine	[]	[]	[]	[]	[]
Corrosion Control	[]	[]	[]	[]	[]
Avionics	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

Industrial:

Warehouses	[]	[]	[]	[]	[]
Petroleum Op	[]	[]	[]	[]	[]
Hydrant Fueling	[]	[]	[]	[]	[]
POL OP Stor	[]	[]	[]	[]	[]
Explosive Storage	[]	[]	[]	[]	[]
Hazardous Storage	[]	[]	[]	[]	[]
PMEL	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			

Hush House #2 (contd):

Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
----------------------	----------------------	------------------------	----------------------	------------------------

Administrative:

Wing/Group HQ	[]	[]	[]	[]	[]
CBPO	[]	[]	[]	[]	[]
Civilian Personnel	[]	[]	[]	[]	[]
Family Services	[]	[]	[]	[]	[]
Data Proc	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Community:

Stores	[]	[]	[]	[]	[]
Exchange Sales	[]	[]	[]	[]	[]
Bank/Credit Union	[]	[]	[]	[]	[]
Post Office	[]	[]	[]	[]	[]
Schools	[]	[]	[]	[]	[]
Chapel	[]	[]	[]	[]	[]
Museum	[]	[]	[]	[]	[]
Library	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Medical:

Hospital	[]	[]	[]	[]	[]
Dental Clinic	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Housing:

Family Housing	[]	[]	[]	[]	[]
TLF	[]	[]	[]	[]	[]
BOQ	[]	[]	[]	[]	[]
UEPH	[]	[]	[]	[]	[]
VoQ	[]	[]	[]	[]	[]
VAQ	[]	[]	[]	[]	[]
[] Other	_____				
(specify)	_____				
f	_____				

Hush House #3:

Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
----------------------	----------------------	------------------------	----------------------	------------------------

Aircraft Maintenance:

Test Cell	[]	[]	[]	[]
Hush House	[]	[]	[]	[]
Gen Purp	[]	[]	[]	[]
Jet Engine	[]	[]	[]	[]
Corrosion Control	[]	[]	[]	[]
Avionics	[]	[]	[]	[]
[] Other	_____			
(specify)	_____			
f	_____			

Industrial:

Warehouses	[]	[]	[]	[]
Petroleum Op	[]	[]	[]	[]
Hydrant Fueling	[]	[]	[]	[]
POL OP Stor	[]	[]	[]	[]
Explosive Storage	[]	[]	[]	[]
Hazardous Storage	[]	[]	[]	[]
PMEL	[]	[]	[]	[]
[] Other	_____			
(specify)	_____			
f	_____			

Administrative:

Wing/Group HQ	[]	[]	[]	[]
CBPO	[]	[]	[]	[]
Civilian Personnel	[]	[]	[]	[]
Family Services	[]	[]	[]	[]
Data Proc	[]	[]	[]	[]
[] Other	_____			
(specify)	_____			
f	_____			

Hush House #3 (contd):

Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
----------------------	----------------------	------------------------	----------------------	------------------------

Community:

Stores	[]	[]	[]	[]	[]
Exchange Sales	[]	[]	[]	[]	[]
Bank/Credit Union	[]	[]	[]	[]	[]
Post Office	[]	[]	[]	[]	[]
Schools	[]	[]	[]	[]	[]
Chapel	[]	[]	[]	[]	[]
Museum	[]	[]	[]	[]	[]
Library	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

Medical:

Hospital	[]	[]	[]	[]	[]
Dental Clinic	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

Housing:

Family Housing	[]	[]	[]	[]	[]
TLF	[]	[]	[]	[]	[]
BOQ	[]	[]	[]	[]	[]
UEPH	[]	[]	[]	[]	[]
VoQ	[]	[]	[]	[]	[]
VAQ	[]	[]	[]	[]	[]
	[]	Other _____			
	(specify)	_____			
	f	_____			

13. Are their off-site land uses near (within 5000 ft) of the Hush House?

☐ Yes

☐ No*

*Go to question 17

If so, what type?

<u>#1</u>	<u>#2</u>	<u>#3</u>	
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Rural_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Industrial_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Business_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Public areas/open space_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Institutional_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Housing_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Other (please specify): #1_____
			#2_____
			#3_____

14. How far are these buildings from the Hush House? [give distance (feet) and compass position (degrees from north) from the Hush House, and size (square feet) of land use]

Hush House #1:

	<u>Distance</u>	<u>Orientation</u>	<u>Size</u>
Rural	_____	_____	_____
Industrial	_____	_____	_____
Business	_____	_____	_____
Public	_____	_____	_____
Institutional	_____	_____	_____
Housing	_____	_____	_____
Other	_____	_____	_____

Hush House #2:

	<u>Distance</u>	<u>Orientation</u>	<u>Size</u>
Rural	_____	_____	_____
Industrial	_____	_____	_____
Business	_____	_____	_____
Public	_____	_____	_____
Institutional	_____	_____	_____
Housing	_____	_____	_____
Other	_____	_____	_____

Hush House #3:

	<u>Distance</u>	<u>Orientation</u>	<u>Size</u>
Rural	_____	_____	_____
Industrial	_____	_____	_____
Business	_____	_____	_____
Public	_____	_____	_____
Institutional	_____	_____	_____
Housing	_____	_____	_____
Other	_____	_____	_____

15. Has there been any response from off-site residents about vibrations or noises from the Hush House(s)?

☐ Yes

☐ No*

*Go to question 17

If so, which land uses have been affected?

#1	#2	#3	
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Rural_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Industrial_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Business_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Public areas/open space_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Institutional_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Housing_____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Other (please specify): #1_____
			#2_____
			#3_____

16 Were any of the following concerns voiced? (record on matrix below)

- Fear of damage to the buildings or its contents (window rattling, building shaking?)
- Interference with the use of sensitive equipment?
- Interference with conversation or other activities?
- Long-term effects on health from subsonic vibrations?
- Concerns regarding noise associated with initiation of the after-burner testing mode.
- Other.

Hush House #1

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
Rural	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Industrial	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Business	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Public	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Institutional	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Housing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

☐ Other_____

(specify) _____

Hush House #2

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
Rural	[]	[]	[]	[]	[]
Industrial	[]	[]	[]	[]	[]
Business	[]	[]	[]	[]	[]
Public	[]	[]	[]	[]	[]
Institutional	[]	[]	[]	[]	[]
Housing	[]	[]	[]	[]	[]
Other	[]	[]	[]	[]	[]

[] Other _____
 (specify) _____
 f _____

Hush House #3

	Bldg. Damage a	Sens. Equip. b	Conver- sation c	Lg-Tm Health d	Noise/ Startle e
Rural	[]	[]	[]	[]	[]
Industrial	[]	[]	[]	[]	[]
Business	[]	[]	[]	[]	[]
Public	[]	[]	[]	[]	[]
Institutional	[]	[]	[]	[]	[]
Housing	[]	[]	[]	[]	[]
Other	[]	[]	[]	[]	[]

[] Other _____
 (specify) _____
 f _____

17. (Refer to Question @b). Does there seem to be unique vibration and acoustic problems created from operating more than one Hush House at once?

[] Yes [] No

* Go to question 18

Describe: _____

PARTICIPANTS IN HUSH HOUSE SURVEY

<u>Base</u>	<u>SAC BASES</u> <u>Contact</u>
Griffith AFB	Mr. Coulthart
McConnell AFB	Lt. Calvin Wilkin
Minot AFB	Kevin P. Nelson
	MAC BASES
McChord AFB	Ralph Pittman
McGuire AFB	Marty Eisenhart
	AFLC BASES
Hill AFB ¹	Marge Williams
Kelly AFB	Ed Hook
McClellan AFB	Ray Henderson
Wright-Patterson AFB	Lance Groola
	TAC BASES
Bergstrom AFB	Tim Knapp
Cannon AFB	Jim Richards/Pat Campbell
Homestead AFB	Roland Allen
Langley AFB ¹	Tom Whittkamp
Luke AFB ¹	Bob Robertson/John Forrest
MacDill AFB	Linda Hoffman/Harry Knudson
Mountain Home AFB ¹	Don Pachner
Nellis AFB	Capt. Richardson
Tyndall AFB ¹	David Stokes/MSG Beberry
	AFR BASES
Dobbins AFB ¹	Bruce Ramo
	ANG BASES
Andrews AFB	Capt. David Sanchez
Burlington international Airport ¹	Major Erwin Waibel
Fort Smith Municipal Airport ¹	Lt. Col. Phillip Gore
Hector Field	Lt. Col. Donald Caswell
Hulman Field Regional Airport	Capt. Michael McGowen
Jacksonville International Airport	Capt. Bill Norton
Joe Foss Field ¹	Major Thomas Molohon
Lambert Field ¹	Major Roy T. Vanhee
March AFB	Lt. Col. Richard Schmitt
McConnell AFB	MSG Richard Wombacher
McEntire ANG Base	Major James Berry
Otis And Base ^{1,2}	Major Paul Brogna
Selfridge ANG Base	Major Robert Lukas

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VOLUME III:

**HUSH HOUSE INFRASONIC AND
SEISMIC EMISSIONS PRODUCE
BY F-100 ENGINE TESTS AT
LUKE AFB, ARIZONA AND
BURLINGTON IAP, VERMONT**

James T. Beaupre
Francis A.
Crowley

Weston Observatory
Department of Geology and
Geophysics
Boston College
331 Concord Rd.
Weston, Massachusetts 02193

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Note: The seismo-acoustic data used in this report was acquired under contract F19628-84-C-0011 sponsored by the Air Force Geophysics Laboratory (AFGL/AFSC).

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I. INTRODUCTION AND FINDINGS

Surface pressures and seismics produced by the Luke AFB Hush House are measured for F-100 engine runs at military power and with afterburner. The study undertaken here is a continuation of work initiated earlier by the Air Force Geophysics Laboratory (AFGL) to optimize site selection by forecasting vibro-acoustics produced by Hush House operations. The present effort seeks to locate the "Hush House source" and describe its emission in a flat, open area. To this end, surface observations taken by AFGL at Luke AFB are known to be seismics excited by infrasonics emitted from a small source region 10 meters over the mouth of the augments tube.

The direct ground path at Luke AFB is a weak contributor to ground vibrations excited by hush House operations. For an acoustic (atmospheric) source, source strength and the specific acoustic impedance of the air-ground boundary control seismic intensity. Impedance values obtained at Luke AFB are incompatible with a Hush House that acts directly on the ground to shake the neighboring area through its foundation. Seismic (ground) sources at this site, because of air-coupling, will excite narrow-band surface infra-sonics with an impedance maximum at 12.5 Hz. Conversely, an acoustics source, such as the hush House, excites a narrow-band ground motion with an impedance minimum at this same frequency. The frequency for coupling acoustics and seismics is a site dependent quantity. It is determined by the material constants of the ground, its layering and the phase velocity of the load. For a distance of 100 meters from the Hush House, the velocity of the load is quite close to the speed of sound in air (1), (6), (9).

II. THE MEASUREMENTS

SYSTEM TRANSFER FUNCTION

Figures 1 a & b give typical transfer functions for the AFGL seismic and pressure hardware used in this study. The transfer function for each channel is obtained from the analysis of calibration transients inserted into the system with the sensors in place, just prior to and following measurements (2).

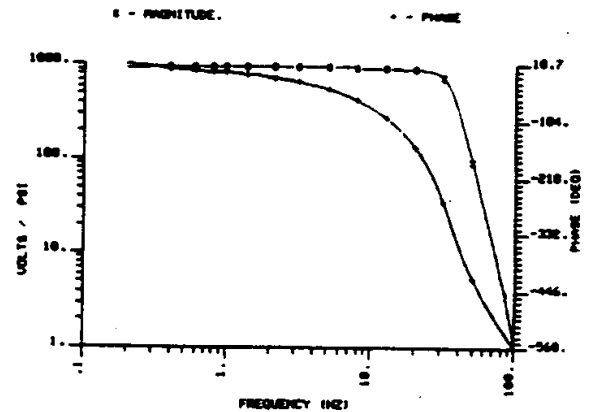


FIGURE 1A-SYSTEM RESPONSE (PRESSURE)

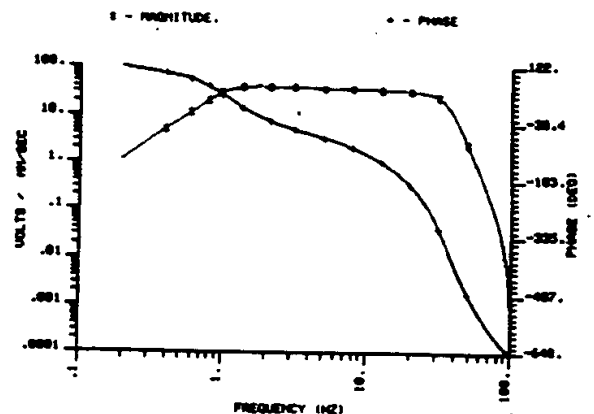
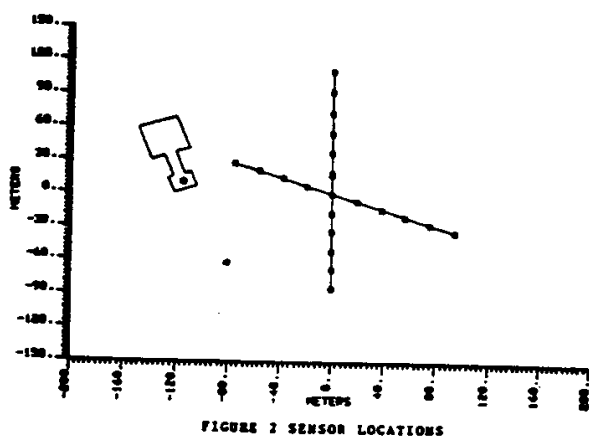


FIGURE 1B-SYSTEM RESPONSE (SEISMIC)

Two sets of measurements are analyzed, Figure 2. One is obtained from a string of sensors (shown as squares) that run radially from the Hush house; it is used to locate the source and establish the propagation and attenuation attributes of the pressure field. The other sensor string is largely tangential; it provides a data base to determine source properties with azimuth. Lately, the best source location for "Hush House" acoustics is indicated.



DYNAMIC RANGE

In addition to hardware response, particular attention is given to estimating the useful passband for the measurements. Under this analysis, "noise" caused by wind and hardware sources, being largely additive and uncorrelated between "nearly collocated sensors", is isolated from a coherent acoustic "signal" (3). The dynamic range of the system is expressed as the square root of the ratio of the spectrum of the coherent acoustic "signal" to the spectrum of the incoherent wind and hardware "noise" for engine runs at military power and also runs with afterburner, Figures 3 a & b. The useful passband of

the system is then defined by the frequencies of the signal is demonstrably an order of magnitude greater than the noise [$S/N > 10$]. The useful band of pressure measurements is found to lie between 2 and Hz. It is worth noting that a somewhat larger signal-to-noise bandwidth product (information content) is obtained for the stronger infrasonics generated by afterburner operations, as should be expected from such a construction.

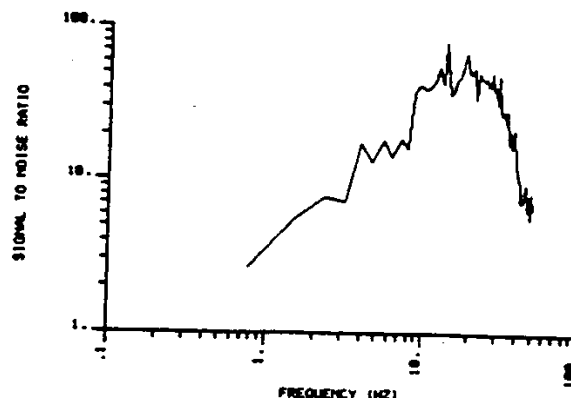


FIGURE 3A - SIGNAL/NOISE RATIO FOR MILITARY POWER

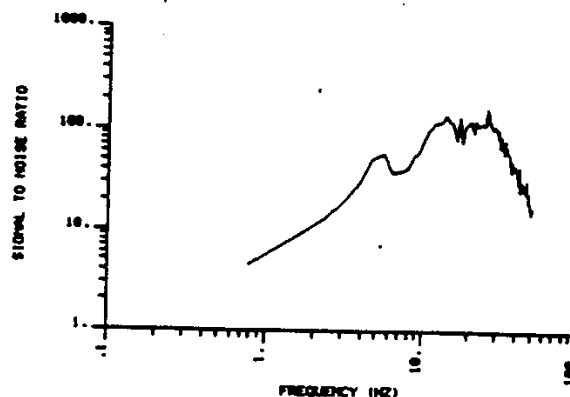


FIGURE 3B - SIGNAL/NOISE RATIO FOR AFTERBURNER

III. HUSH HOUSE PRESSURE MODEL

orientation, θ , from the Hush House is modeled as the combination of a stationary statistical source, $p(\theta;t) \sim N(0,1)$, with a site response, $\phi(a, \theta; t)$ that incorporates all propagation and boundary effects for a path defined by the source and measurement positions (4).

$$p(a, \theta; t) = \phi(a, \theta; t) * p(\theta; t) * N(0,1)$$

where the symbol $*$ denotes convolution.

For the flat, open area around the Hush House near the runway at the Luke AFB, propagation is treated to be independent of azimuth during periods of low wind, giving:

$$p(a, \theta; t) = \phi(a, \theta; t) * p(\theta; t) * N(0,1)$$

Hush House surface pressure is now modeled as a standard normal, independent, zero mean process cascaded into an azimuth sensitive source operator and largely range dependent site propagation term.

For the weather conditions and measurement ranges at Luke AFB, acoustic propagation is nondispersive with a sound speed near 340 meter/second. To a first approximation, pressure around the reference distance $p = a$ for a flat, open site is represented by small source, far-field spherical acoustics (5).

$$P(r;w) = a/r.[P(a;w).exp i[k(r-a)]]$$

$P(r, \theta; w)$, the Fourier transform of the surface pressure time history, $(p_r, \theta; t)$, measured at some distance r and orientation θ from the source then relates to the source term $P(a, \theta; w)$ at the reference distance, a , as:

$$P(r, \theta; w) = a/r.[P(a, \theta; w).exp(ik(r-a))] \text{ where}$$

the wave number k , phase velocity c , and angular frequency w , are related by $c=w/k$ and attenuation is as the first power of the range.

For a flat, dense earth, the ground almost totally reflects the incident pressure without a phase change for all but air-coupled frequencies(6).

Hence, for flat open areas, ground motion excited by air loads is typically small or narrow-banded with a surface pressure of about twice the free-field term.

For forecasts in complicated reverberating areas ($P_a, \theta; w$) can be obtained empirically. For a continuing source like the Hush House, it shapes an independent normal process $N(0,1)$ to match the surface pressure spectra observed at a reference distance a , and orientation θ , from the source. It includes all modifier terms due to the interface. Extrapolation around the reference distance is then approximated by spherical acoustics in areas free of severe scattering and focusing.

For some orientations at Luke AFB, infrasonics produced by F-100 engines conform to the spectral shape of a free standing jet (7). The results and the manner of comparing Hush House periodograms against standards form "jet" pressure spectra are summarized in Appendix A. It is concluded that Hush House emissions cannot be modeled as a vertical annular jet, for unlike a jet, Hush House source spectra clearly depend on azimuth.

IV. SOURCE LOCATION

SPACIAL COHERENCY

Source location estimates for Hush House emission given here rest on maximizing the spatial coherency of the observed pressure field. Spatial coherency is a positive quantity between zero and one computed from the ratio of the magnitude of the vector sum of pressure spectral estimates taken over a set of measurement points, compensated for propagation delay, to the value of the corresponding secular sum. Under this definition, the upper-bound value, units, completely accounts for the observations as a disturbance propagating outward from a source region at a phase

velocity given by $c = w/k$

$$\phi(f,k) = \frac{r(P(r,\#,f) \cdot \exp[ikr])}{r(P(r,\#,f))}$$

PHASE VELOCITY

Figure 4 depicts the spatial coherency estimate for the pressure field excited by the Hush House at the frequency, $f = 16.41$ Hz., after phase compensating the radial line data for "k" delays from a source region over the south mouth of the augmentor tube.

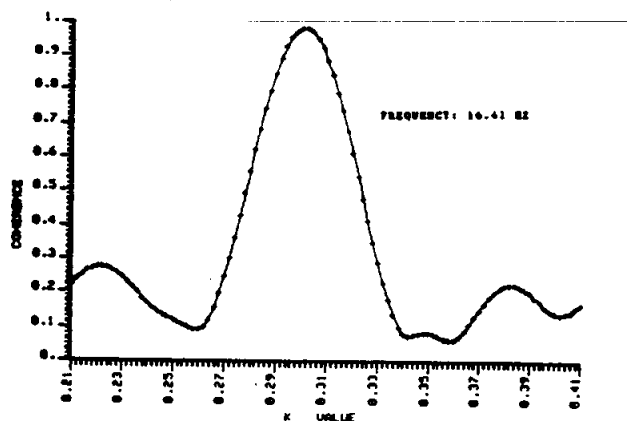


FIGURE 4 - SPACIAL COHERENCY ESTIMATE

location and set of observations is clearly a maximum for $k = .300$ cycles/meter. The wave number value sets the phase velocity for coherently propagating pressure at this frequency to be 344 meters/second. The process of adding vector values, compensated for propagation delay and selecting k by the coherency maximum is repeated for each frequency. The resulting frequency wave number, (f,k) pairs define propagation for the coherent pressure term. The "best" source location is the position that leads to the absolutely

highest coherency estimate; the source that best accounts for the pressure observations.

V. SURFACE PRESSURE ATTRIBUTES

The spatial coherence for surface pressure at Luke AFB is an absolute maximum for an acoustic source 10 meters over the Hush House augmentor tube, independent of operating level, Table 1. Surface pressures from this region propagate uniformly outward without change in shape. On the average, better than 95% of the pressure measured in the band 6 Hz. To 36 Hz. can be satisfied by acoustics coming from this source region during afterburner operations.

TABLE 1

MEDIAN COHERENCIES FOR RADIAL LINE DATA:

(half octave estimate)

SOURCE #	COHERENCY	DATA FILE	ELEVATION (METERS)
0	.9125	13301#	10
1	.9921	13311#	10
2	.9842	13321#	10
3	.9547	13331#	10
4	.9375	13341#	10

Figure 5a locates the special coherency maxima of the pressure field for the "best" source in (f,k) space. The points are satisfied by a straight line fit through the origin with a slope of 340 meters/second. The observed pressures are found to propagate at a constant velocity, quite independent of frequency. The associated "coherency maxima" for the "best" source region (Source #1) are given in Figure 5b. The coherence shown here are almost as large as those used to estimate the system's dynamic range. In addition, trial locations off the mouth of the augmentor

tube along the Hush House centerline, or at different heights over the deflector, lead to lower coherencies and inconcsistent velocity estimates, Table 1.

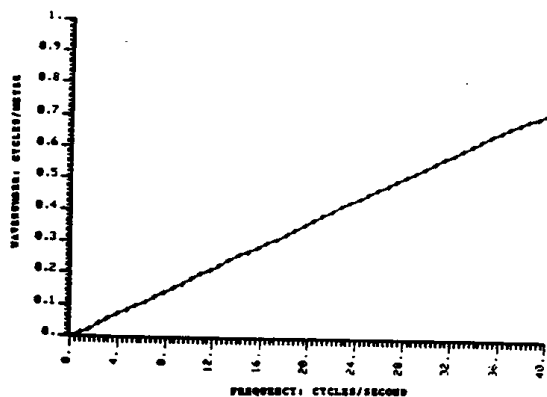


FIGURE 5A - SPACIAL COHERENCY MAXIMA

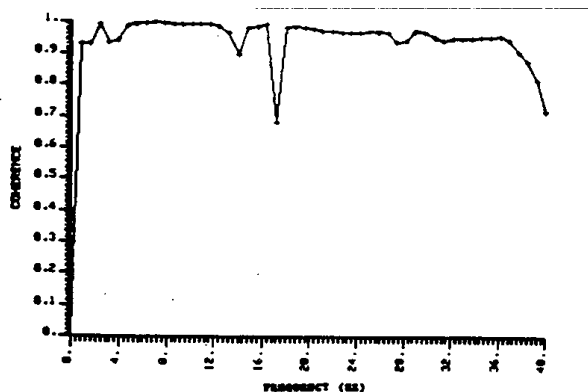


FIGURE 5B - ABSOLUTE COHERENCY MAXIMA

It is worth noting that the results found here

It is worth noting that the results found here for most of the infrasonics and all of the low frequency acoustics conflict with the proposition that Hush House missions need be represented by a pair of sources located at each end of the augmenter tube (8). The mullet-point assumption (Source #1 and #2) is important because it has become a standard feature for

locating Hush House acceptance measurements and underlies interferences about hush House level with range and azimuth.

Spatial coherency maxima that use measurements along the tangential line are substantially less than unity, Figure 6. Surface pressures around the Hush House are spatially incoherent when based on points at widely different orientations. Coherent estimates that use the tangential line measurements still have an absolute maxima for a source region over the augmenter tube with propagation delays satisfied by a phase velocity close to the speed of sound in air. However, when these estimates are contrasted to the results obtained earlier using stations clustered at one heading, it is clear that the Hush House source pressure, the pressure remaining after compensation for propagation delay, does not radiate uniformly in phase with azimuth.

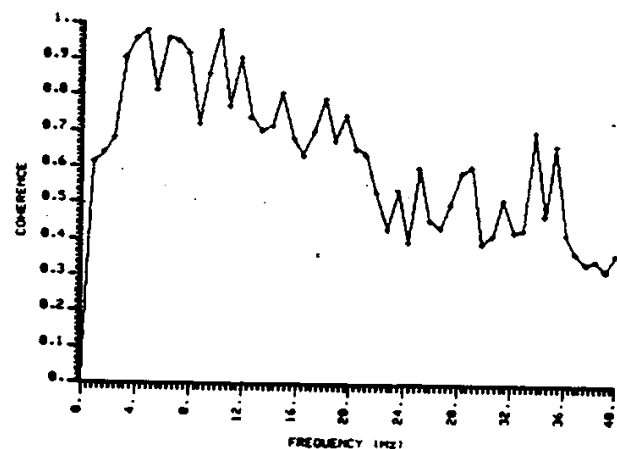


FIGURE 6 - TANGENTIAL SPACIAL COHERENCY MAXIMA

The low coherencies found here differ markedly from the high "temporal" coherencies that use surface pressure measurements from station pairs at different orientations, Figure 7. The high temporal

coherency values above 8 Hz. for station pairs spaced at widely different headings show source phase differences to be time invariant for all but a secondary disturbance centered around 5 Hz. The Hush House radiation pattern in phase (as well as in amplitude) depends on azimuth largely in the manner of a single source. Looking ahead, infrasonic attenuation being inversely proportional to the first power of distance, points to a source region that is quite well compared to the reference distance, 100 meters.

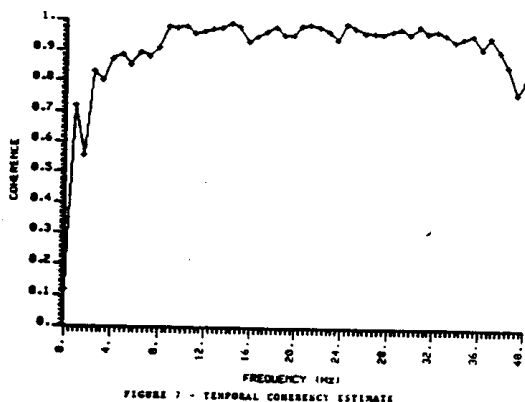


FIGURE 7 - TEMPORAL COHERENCY ESTIMATE

ATTENUATION

Far-field spherical propagating without internal loss attenuate surface pressure as $1/r$. Departures from this simple attenuation model can be readily examined once the Hush House source is properly located. Figure 8 gives pressure amplitudes to a best fitting power law with distance for surface pressure amplitudes at a frequency of 14.06 Hz. for a F-100 engine operating at military power. At this frequency and orientation, the observed pressures are well satisfied by spherical spreading. Two parameters of the pressure are computed from the amplitude data at each frequency, Figures 9 A & b. The first is a

least squares estimate of attenuation to a simple power law in r : the second measures the "fit" between a linear relation in $\ln |p(r,f)|$ and in (r) . For spherical waves measured in the absence of noise, the slope is -1.0 and the magnitude of the fit given by the correlation coefficient is unity.

The slope due to spreading at a flat, open site can be expected to lie between near-field contributions with a slope of -2.0 and cylindrical boundary waves with a slope of -0.5.

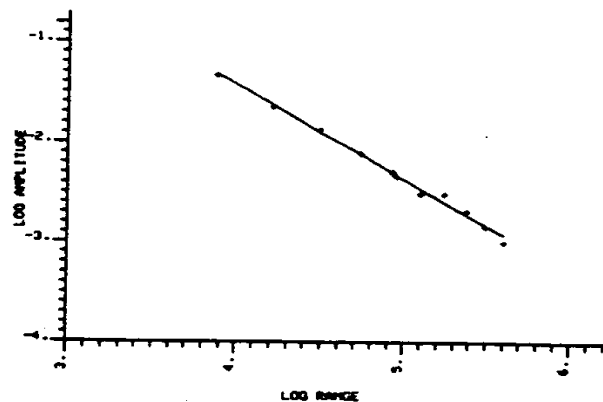


FIGURE 8 - ATTENUATION WITH RANGE

For the AFGL Luke AFB data, attenuation tends to have a positive slope with frequency, i.e., attenuation decreases with increasing frequency, see Table 2.

TABLE 2

ATTENUATION DEPENDENCY WITH FREQUENCY

MILITARY POWER	RUN #	SLOPE
	0	7.0063 E-03
	1	10.8365 "
	2	12.7698 "
	3	9.5988 "
AFTERBURNER	0	3.3284 "
	1	6.1004 "
	2	2.9157 "
	3	5.6778 "

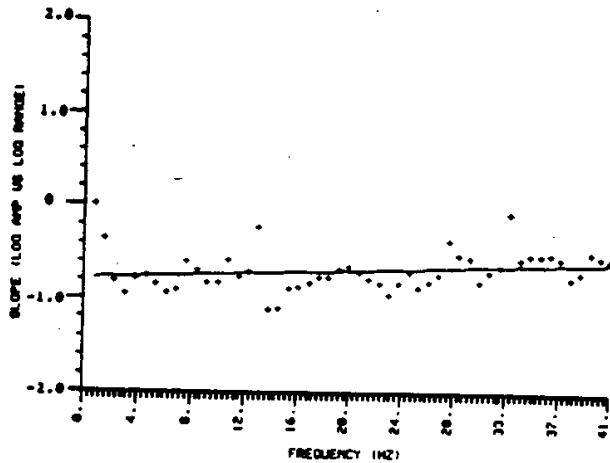


FIGURE 9A - SPACIAL ATTENUATION: SLOPE VS FREQUENCY

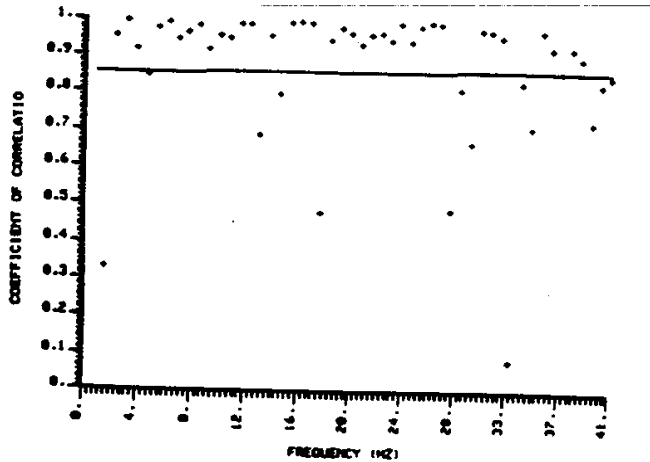


FIGURE 9B - SPACIAL ATTENUATION (FIT VS FREQUENCY)

The constant velocity measured earlier does not support focusing to explain low attenuation. Surface pressure at infrasonic frequencies attenuates much like spherical waves from a small source region. Attenuation at acoustic frequencies is consistently closer to cylindrical. The observed attenuation can be explained by a slim vertical line source centered over the augmentor tube or a bounded wave set up by a weak, undetected temperature gradient near the surface.

As a practical matter and for short extrapolations, the change in attenuation with frequency and the departure from spherical spreading is relatively small for infrasonics; pressure measurements at 100 meters can be extrapolated radially a wavelength out from a reference pressure as a spherical acoustics from a small region just above the augmentor tube mouth with only small error. However, extrapolation as spherical acoustics over several wavelengths is not well supported for any frequency. Further, non radial extrapolations in support of hush House siting must also deal with a poorly defined azimuth source term.

SOURCE RADIATION PATTERN

Stable power spectra estimates of surface pressure (DOF = 18) measured at a distance of 116 meters and heading of 335 degrees from the "best" Hush House source location are given in Figures 10 and 11 for a F-100 engine operating at military power and then with afterburner. Hush House spectra grossly follow the characteristic shape of emissions from an annular "jet". The match is imperfect. The main mismatch to the jet "ball shape" spectral characteristic is caused by a persistent secondary maximum at 6 Hz; more than an octave below the main peak.

The main difference between the spectra for the two operating conditions is in level. The overall power level for engine runs with afterburner is an order of magnitude greater than that for runs at military power. A second and less conspicuous difference is a shift in frequency. The frequency of spectral maximum for runs with afterburner is higher than the corresponding frequency for runs at military power. In either case, the peak spectral power is below 20 Hz. A description of hush House performance and its environmental impact solely in terms of

"suppressed" acoustics (> 20 Hz.) ignores this peak. Infrasonics (> 20 Hz.) generated by Hush House operations are the more relevant consideration for treating ground (and building) vibro-acoustics at Luke AFB).

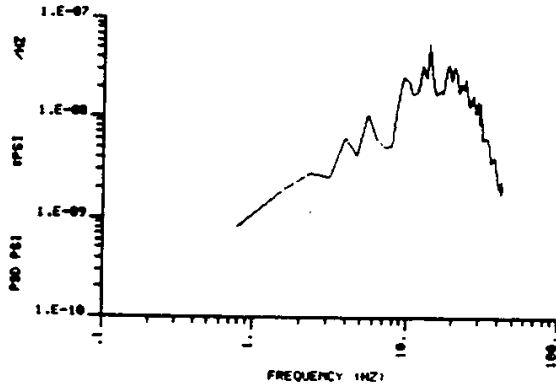


FIGURE 10 - SPECTRA FOR MILITARY POWER

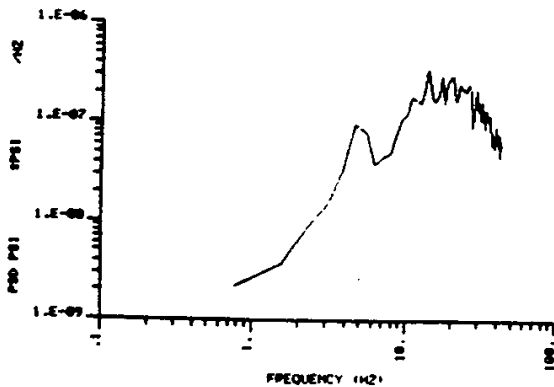


FIGURE 11 - SPECTRA FOR AFTERBURNERS

sensitive. The infrasonic source pattern does not carry over unchanged into the acoustic range. For example, the low acoustic values at the front of the hush House at 30 degrees or more do not carry into the infrasonic range.

Clearly, Hush House orientation can have a major impact on the vibro-acoustics produced in neighboring facilities. However, an orientation that mitigates acoustics can easily aggravate vibration level.

Figure 12b shows relative source phase with azimuth also under the assumption of left-right symmetry for the same "corrected" afterburner data determined from cross spectra. Large phase changes can be associated with the amplitude lobes at 340 and 20 degrees.

VI. NORMAL SURFACE IMPEDANCE

The magnitude of the impedance of the ground to the reference range a, under the action of the Hush House is calculated from the ratio of the interference pressure to the vertical particle velocity of the ground. Its value for a low velocity, flat layered earth depends on phase velocity near the speed of sound in air, the dependence on wave number can be suppressed to give,

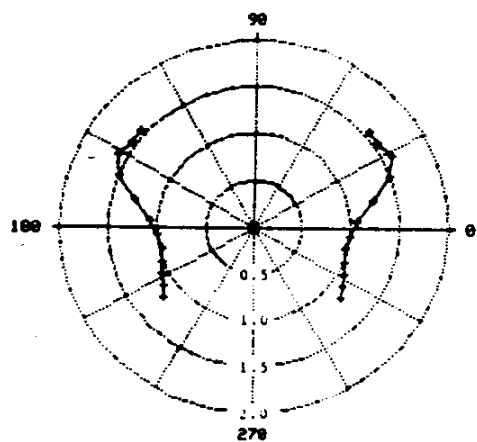
$$\begin{aligned} \text{F.T. } p(a, \#; t) &= p(a, \#; w) \\ \text{F.T. } v(a, \#; t) &= v(a, \#; w) \end{aligned}$$

$$Z(a, \#, w) = p(a, \#; w) / v(a, \#; w)$$

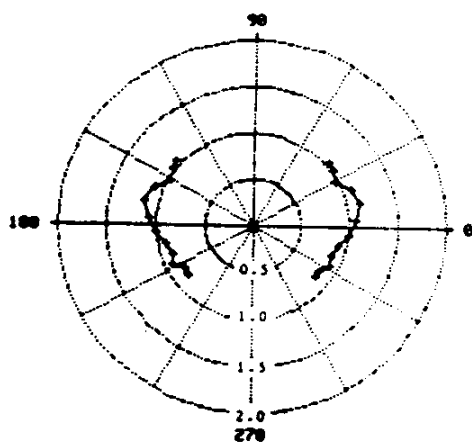
Surface pressures taken along the tangential line are compensated in amplitude and phase to a constant distance of 116 meters from the "best source" location. Figure 12a shows the ratio of infrasonic level against the value at a heading of 335 degrees for several frequencies. The radiation pattern is frequency

Due to the large density between the air and ground, motion is typically small, leaving impedance a large value for acoustic sources. Figure 13 is the magnitude of the admittance, $1/|Z(r, w)|$ obtained during Hush House operations.

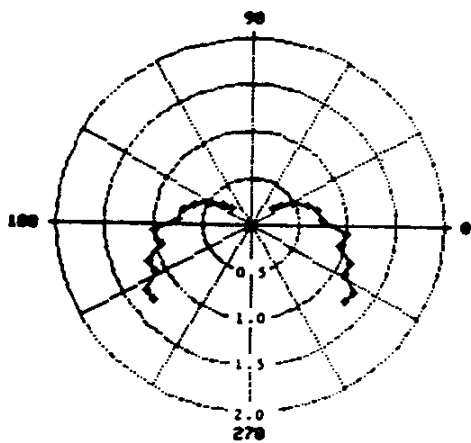
FIGURE 12A -RELATIVE AMPLITUDE



FREQUENCY
6.250 HZ



FREQUENCY
10.937 HZ



FREQUENCY
29.687 HZ

FIGURE 12B - RELATIVE PHASE

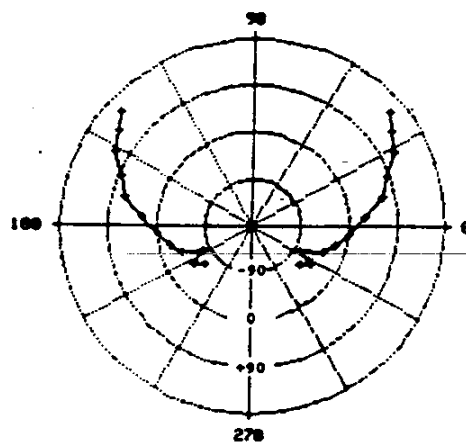
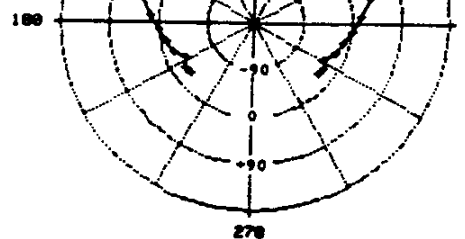
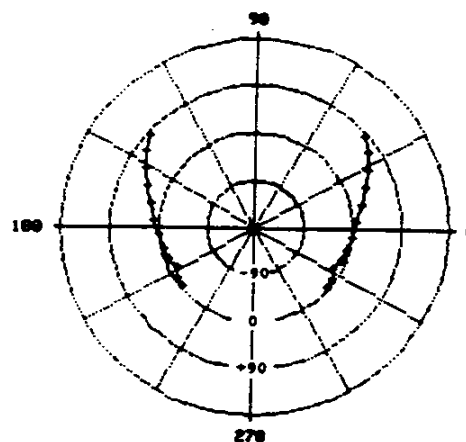


FIGURE 12C - RELATIVE PHASE

FIGURES 12A & 12B - HUSH HOUSE SOURCE PATTERNS

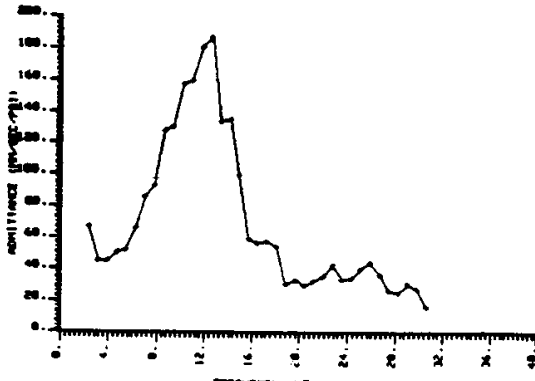


FIGURE 13
GROUND IMPEDANCE MAGNITUDE DETERMINING THE LUKE AFB HUSH HOUSE

For frequencies off the air-coupled term, admittance is small (between 15 and 30 millimeters/second/psi). For areas that support low velocity Rayleigh waves, admittance at air-coupling can be enhanced an order of magnitude by atmospheric sources. The maximum admittance measured at Luke AFB is 186 millimeters/second/psi. It is found at 12.5 Hz. Seismics excited by the hush House exhibit the characteristic response of a low velocity, flat-layered area to an atmospheric source (1,6,9).

The direct ground path is only a weak contributor to the vibro-acoustic environment measured here. For above ground structures at Luke AFB, it has been demonstrated that Hush House induced vibrations in buildings can be predicted solely through the building's response to infrasonics produced by low altitude explosions (10.)

Also, it is clear from the raw time histories of air shots obtained from the companion study that building motion from the "fast ground path" is only weakly excited by atmospheric sources, Figure 14. The overwhelming bulk of the motion follows, and is the direct result of the acoustic load and the site's

sensitivity to a load moving over its surface not the speed of the ground "Rayleigh" wave, a dispersive boundary wave whose attributes depend on the site's geological structure (9).

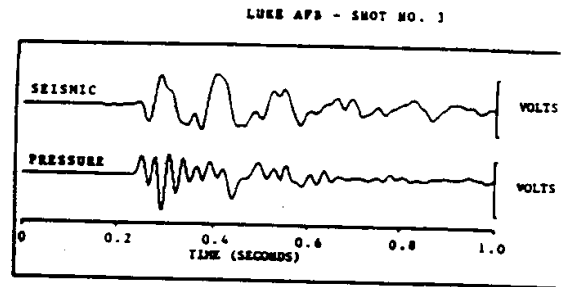


FIGURE 14
VIBRO-ACOUSTIC OBSERVATIONS FOR A LOW ALTITUDE AIRBURST

ENVIRONMENTAL IMPACT

Clearly, a site's sensitivity to Hush House operations can be aggravated or ameliorated by the air-coupled ground term and building responses coaligning or misaligning with peak Hush House infrasonics. However, any serious assessment of the importance of these emissions on environmental quality requires better definition of human response to such stimuli. In addition, its importance to the Air Force requires a definitive statement of need for "quiet" environments (e.g. facility requirements for inertial hardware test and calibration.)

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14. Vibro-Acoustic Observations for a Low Altitude Burst

APPENDIX A - STANDARD FORM SPECTRAL ESTIMATES

Both from physical considerations (A1) and a number of experimental studies (A2), surface pressure spectra from undeflected jets have been shown to exhibit the form

$$4P_o/xw_o(w/w_o+w_o/w)^{-2}$$

with the overall sound power, P_o , proportional to thrust and the frequency at the spectral maximum, w_o , sensitive to the ratio of the jet diameter and the exhaust velocity (Strouhal Number).

The hypothesis that Hush House pressure spectra can be described in terms of "jet" spectra is tested by plotting residuals between calculated periodogram coefficients and a standard form "jet" spectra, as a Rayleigh distribution, the expected distribution had we tested periodogram estimates from a stationary Gaussian process about its "true" spectral value, Figure A1(A3). Figure A2 is the distribution observed for the residuals plotted against the Rayleigh distribution. The hypothesis is tested by simply accepting or rejecting when the values fall along the indicated straight line.

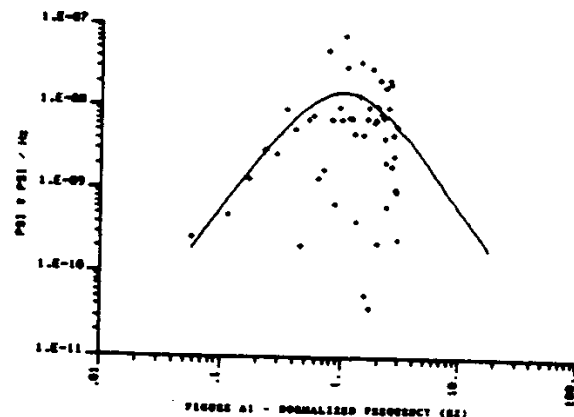


FIGURE A1 - NORMALIZED FREQUENCY (Hz)

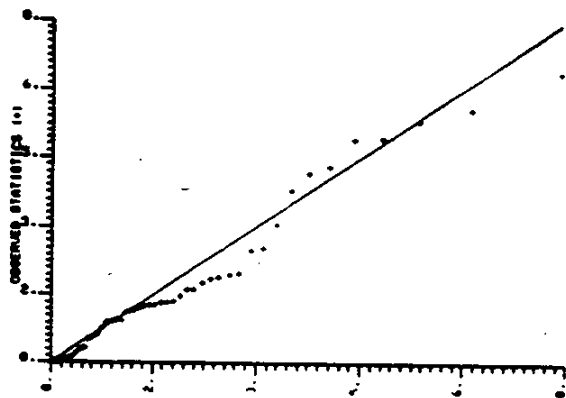


FIGURE A2 - THEORETICAL STATISTICS (-).

- A2 Acoustic Loads Generated by the Propulsion System, NASA SP-8072, June 1971.
- A3 Hartnett, E and Carleen, E., Characterization of Titan III-D Acoustic Pressure Spectra by Least-Squares Fit to Theoretical Model, AFGL-TR-80-0004, Jan. 1980.

A second test of surface pressures produced by the hush House operations having standard form "jet" characteristics uses a figure of merit, M , calculated from the ratio of the variance of the spectral residuals to the standard form spectra squared. The value for the figure of merit for the expected distribution for a jet, is unity. The test for accepting that a spectrum has a "jet" form is that M lies in the range $.6 \leq M \leq 2.0$, an acceptance range established by M values obtained from simulation.

Table 1A is a compilation of results for runs at military power and with afterburner. Individual periodgrams often exhibit standard form "jet" spectra characteristics. However, unlike an annular jet, the Hush House does not radiate the same spectra in all directions. Hush House infrasonics do not exhibit the properties of a pressure field produced by a vertical (undeflected) jet.

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APPENDIX - TABLE 1A

COMPILATION OF RESULTS: MILITARY POWER

COMPILATION OF RESULTS: AFTERNOON

SCANS SHIPPED: CHAM	0 READING (000)	RANGE (01)	FLIGHT OF HEAT (02)	PS ESTIMATE (03)	W/STATION POWER (04)	W/STATION POWER (05)
1	-39.5	149.4	1.07	0.370E-07	94.30	92.32
2	-34.1	139.3	1.73	0.444E-07	94.98	93.33
3	-27.9	130.5	0.74	0.408E-07	95.72	93.36
4	-20.9	123.5	0.95	0.435E-07	96.44	94.45
5	-13.2	118.5	0.70	0.435E-07	96.75	94.45
6	-5.0	115.9	0.71	0.435E-07	97.04	94.74
7	4.1	115.7	0.72	0.421E-07	96.77	94.19
8	13.0	118.5	1.24	0.408E-07	96.44	93.90
9	21.3	123.9	1.33	0.344E-07	96.25	93.54
10	28.7	131.5	0.40	0.370E-07	96.41	94.91
11	35.3	141.3	0.47	0.390E-07	97.45	96.91
12	41.1	152.0	0.47	0.223E-07	97.45	99.17
SCANS SHIPPED: 000						
1	-39.5	149.4	2.21	0.311E-07	93.15	90.04
2	-34.1	139.3	1.03	0.340E-07	93.50	90.50
3	-27.9	130.5	1.05	0.334E-07	94.30	91.33
4	-20.9	123.5	0.87	0.435E-07	95.07	92.31
5	-13.2	118.5	0.68	0.307E-07	95.38	93.40
6	-5.0	115.9	1.27	0.401E-07	96.22	95.44
7	4.1	115.7	1.14	0.390E-07	96.09	95.05
8	13.0	118.5	0.78	0.435E-07	96.45	95.18
9	21.3	123.9	0.62	0.435E-07	97.07	95.67
10	28.7	131.5	0.44	0.370E-07	97.45	96.91
11	35.3	141.3	1.37	0.283E-07	97.44	96.47
12	41.1	152.0	1.23	0.223E-07	97.44	99.17
SCANS SHIPPED: 1000						
1	-39.5	149.4	0.86	0.440E-07	95.29	96.43
2	-34.1	139.3	1.17	0.340E-07	95.45	97.15
3	-27.9	130.5	0.83	0.475E-07	96.44	97.11
4	-20.9	123.5	1.05	0.490E-07	97.09	97.97
5	-13.2	118.5	0.45	0.475E-07	97.34	97.41
6	-5.0	115.9	0.78	0.101E-06	97.97	97.40
7	4.1	115.7	0.82	0.435E-07	97.07	97.10
8	13.0	118.5	0.78	0.435E-07	97.38	97.77
9	21.3	123.9	0.77	0.370E-07	97.45	97.81
10	28.7	131.5	0.82	0.307E-07	97.45	97.81
11	35.3	141.3	0.84	0.440E-07	97.45	97.81
12	41.1	152.0	0.87	0.351E-07	97.45	97.81
SCANS SHIPPED: 2000						
1	-39.5	149.4	1.73	0.494E-07	97.45	96.00
2	-34.1	139.3	4.91	0.394E-07	97.09	97.02
3	-27.9	130.5	1.01	0.344E-07	97.01	96.29
4	-20.9	123.5	12.11	0.435E-07	94.33	94.75
5	-13.2	118.5	1.50	0.340E-07	94.49	95.77
6	-5.0	115.9	0.89	0.411E-07	94.92	96.19
7	4.1	115.7	1.53	0.311E-07	95.29	97.11
8	13.0	118.5	2.54	0.411E-07	97.07	97.10
9	21.3	123.9	2.53	0.411E-07	97.07	97.10
10	28.7	131.5	2.53	0.267E-07	97.75	97.11
11	35.3	141.3	1.00	0.267E-07	97.75	97.44
12	41.1	152.0	0.94	0.201E-07	97.75	99.34
SCANS SHIPPED: 3200						
1	-39.5	149.4	1.59	0.351E-07	93.19	93.20
2	-34.1	139.3	1.70	0.301E-07	93.87	93.55
3	-27.9	130.5	1.40	0.397E-07	94.39	92.83
4	-20.9	123.5	1.43	0.441E-07	95.63	93.13
5	-13.2	118.5	2.09	0.475E-07	95.44	91.99
6	-5.0	115.9	2.43	0.440E-07	96.07	91.87
7	4.1	115.7	2.13	0.440E-07	95.94	91.49
8	13.0	118.5	2.13	0.370E-07	96.25	90.47
9	21.3	123.9	1.99	0.370E-07	96.25	90.11
10	28.7	131.5	2.17	0.307E-07	94.23	88.46
11	35.3	141.3	2.05	0.223E-07	93.84	88.42
12	41.1	152.0	2.30	0.190E-07	93.84	88.13
SCANS SHIPPED: 4000						
1	-39.5	149.4	1.00	0.370E-07	94.09	95.72
2	-34.1	139.3	2.01	0.435E-07	95.11	96.29
3	-27.9	130.5	0.77	0.410E-07	95.11	95.47
4	-20.9	123.5	0.87	0.410E-07	96.36	95.88
5	-13.2	118.5	0.85	0.410E-07	96.36	95.44
6	-5.0	115.9	0.95	0.410E-07	96.74	95.88
7	4.1	115.7	0.95	0.410E-07	96.74	95.88
8	13.0	118.5	0.91	0.410E-07	96.74	95.88
9	21.3	123.9	1.02	0.410E-07	96.74	95.88
10	28.7	131.5	1.02	0.410E-07	96.74	95.88
11	35.3	141.3	1.02	0.410E-07	96.74	95.88
12	41.1	152.0	1.02	0.410E-07	96.74	95.88

SCANS SHIPPED: CHAM	0 READING (000)	RANGE (01)	FLIGHT OF HEAT (02)	PS ESTIMATE (03)	W/STATION POWER (04)	W/STATION POWER (05)
1	-39.5	149.4	0.70	0.370E-07	94.30	92.32
2	-34.1	139.3	1.73	0.444E-07	94.98	93.33
3	-27.9	130.5	0.74	0.408E-07	95.72	93.36
4	-20.9	123.5	0.95	0.435E-07	96.44	94.45
5	-13.2	118.5	0.70	0.435E-07	96.75	94.45
6	-5.0	115.9	0.71	0.435E-07	97.04	94.74
7	4.1	115.7	0.72	0.421E-07	96.77	94.19
8	13.0	118.5	1.24	0.408E-07	96.44	93.90
9	21.3	123.9	1.33	0.344E-07	96.25	93.54
10	28.7	131.5	0.40	0.370E-07	96.41	94.91
11	35.3	141.3	0.47	0.390E-07	97.45	96.91
12	41.1	152.0	0.47	0.223E-07	97.45	99.17
SCANS SHIPPED: 000						
1	-39.5	149.4	1.07	0.307E-06	103.30	100.05
2	-34.1	139.3	1.07	0.307E-06	104.37	100.47
3	-27.9	130.5	0.64	0.307E-06	104.37	100.47
4	-20.9	123.5	1.04	0.307E-06	105.57	100.73
5	-13.2	118.5	0.94	0.440E-06	105.62	100.73
6	-5.0	115.9	0.80	0.440E-06	106.00	100.73
7	4.1	115.7	0.80	0.440E-06	106.12	100.73
8	13.0	118.5	0.82	0.440E-06	105.69	100.73
9	21.3	123.9	0.82	0.440E-06	105.69	100.73
10	28.7	131.5	0.94	0.370E-06	105.69	100.73
11	35.3	141.3	0.89	0.370E-06	105.69	100.73
12	41.1	152.0	0.91	0.307E-06	105.69	100.73
SCANS SHIPPED: 1000						
1	-39.5	149.4	2.97	0.917E-06	101.73	100.74
2	-34.1	139.3	2.17	0.917E-06	101.73	100.74
3	-27.9	130.5	1.00	0.917E-06	101.73	100.74
4	-20.9	123.5	1.00	0.917E-06	101.73	100.74
5	-13.2	118.5	4.07	0.917E-06	101.73	100.74
6	-5.0	115.9	2.11	0.917E-06	101.73	100.74
7	4.1	115.7	1.83	0.917E-06	101.73	100.74
8	13.0	118.5	1.70	0.917E-06	101.73	100.74
9	21.3	123.9	1.70	0.917E-06	101.73	100.74
10	28.7	131.5	1.17	0.917E-06	101.73	100.74
11	35.3	141.3	1.41	0.917E-06	101.73	100.74
12	41.1	152.0	0.89	0.917E-06	101.73	100.74
SCANS SHIPPED: 2000						
1	-39.5	149.4	0.81	0.425E-06	104.11	100.96
2	-34.1	139.3	0.74	0.425E-06	104.11	100.96
3	-27.9	130.5	0.63	0.425E-06	104.11	100.96
4	-20.9	123.5	0.63	0.425E-06	104.11	100.96
5	-13.2	118.5	0.63	0.425E-06	104.11	100.96
6	-5.0	115.9	0.63	0.425E-06	104.11	100.96
7	4.1	115.7	0.63	0.425E-06	104.11	100.96
8	13.0	118.5	0.71	0.425E-06	104.11	100.96
9	21.3	123.9	0.74	0.425E-06	104.11	100.96
10	28.7	131.5	0.69	0.425E-06	104.11	100.96
11	35.3	141.3	0.70	0.425E-06	104.11	100.96
12	41.1	152.0	0.81	0.425E-06	104.11	100.96
SCANS SHIPPED: 3200						
1	-39.5	149.4	0.70	0.340E-06	102.82	100.76
2	-34.1	139.3	0.67	0.340E-06	102.82	100.76
3	-27.9	130.5	0.70	0.340E-06	102.82	100.76
4	-20.9	123.5	1.20	0.340E-06	102.82	100.76
5	-13.2	118.5	1.00	0.340E-06	102.82	100.76
6	-5.0	115.9	0.74	0.340E-06	102.82	100.76
7	4.1	115.7	0.71	0.340E-06	102.82	100.76
8	13.0	118.5	0.69	0.340E-06	102.82	100.76
9	21.3	123.9	0.69	0.340E-06	102.82	100.76
10	28.7	131.5	0.69	0.340E-06	102.82	100.76
11	35.3	141.3	0.69	0.340E-06	102.82	100.76
12	41.1	152.0	1.00	0.340E-06	102.82	100.76
SCANS SHIPPED: 4000						
1	-39.5	149.4	1.17	0.870E-06	102.82	100.64
2	-34.1	139.3	1.07	0.870E-06	102.82	100.64
3	-27.9	130.5	1.07	0.870E-06	102.82	100.64
4	-20.9	123.5	0.69	0.870E-06	102.82	100.64
5	-13.2	118.5	0.69	0.870E-06	102.82	100.64
6	-5.0	115.9	0.69	0.870E-06	102.82	100.64
7	4.1	115.7	0.69	0.870E-06	102.82	100.64
8	13.0	118.5	0.69	0.870E-06	102.82	100.64
9	21.3	123.9	0.69	0.870E-06	102.82	100.64
10	28.7	131.5	0.69	0.870E-06	102.82	100.64
11	35.3	141.3	0.69	0.870E-06	102.82	100.64
12	41.1	152.0	0.69	0.870E-06	102.82	100.64

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BACKGROUND AND FOLLOWON STUDIES

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VIBROACOUSTIC FIELD STUDY OF T-10 HUSH HOUSE EMISSIONS

Robert V. Goerke, et al



August 1990

Final Report

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Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008**

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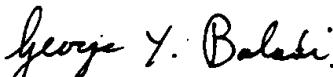
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ROBERT V. GOERKE
Capt, USAF
Project Officer


CLARENCE J. FENNELL
Major, USAF
Chief, Applications Branch

FOR THE COMMANDER


GEORGE Y. BALADI
Technical Advisor
Civil Engrg Rsch Div

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PREFACE

The investigation reported herein was conducted by personnel of the Civil Engineering Research Division (NTE) and the Staff Meteorology Office (UE) of the Weapons Laboratory (WL, AFSC).

This report was prepared and written by Capt. Robert V. Goerke, Capt. Glen J. Pappas, John A. Leverette, Rent R. Anderson, and Dr. Robert E. Reinke of WL/NTE along with 1Lt. Janes M. Nall of UL/UE during the period January 1989 through May 1990. General direction for report preparation was provided by Col. Carl Davidson, Chief, NTE and Dr. George Y. Baladi, Technical Advisor, NTE. Technical editing for the report was done by Celia Ojeda.

Col. Leonard J. Otten was the Commander of WL during the preparation and publication of this report.

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1.0 INTRODUCTION

1.1 OBJECTIVE

This report documents a vibroacoustic field study performed from 27 Jan 90 by the Weapons Laboratory (UL, AFSC) for TAC/DEE of Langley AFB, -Virginia. The study was performed to determine the cause behind the vibrations being felt by homeowners in the vicinity of two AF37/T -10 Hush Houses located on Langley AFB. Data were obtained by performing field surveys using overpressure and seismic recording instrumentation, by recording weather conditions, and by performing structural engineering analyses. From the data, the UL was able to determine the cause of the vibrations and to present possible solutions for attenuating the hush house infrasonic emissions that cause the vibrations.

1.2 BACKGROUND

The T-10 Hush House (Figure 1) was designed to reduce the audible emissions from jet engine testing on the surrounding community and to allow for the siting of the test function closer to the maintenance operations that it supports. In part, the T -10 Hush House emissions are reduced by the transfer of energy from the audible (> 25 Hz) to the infrasonic (< 25 Hz) range. At some locations, these infrasonic emissions from the T -10 Hush Houses have caused harmful vibrations in nearby buildings. At one location, these infrasonic -induced vibrations led to the abandonment of an avionics laboratory (Battis, 1987).

Several vibroacoustic field studies have been conducted on operating T -10 Hush Houses since their first operational use in the early 1980's (Battis, 1985; Battis and Crowley, 1986; Beaupre and Crowley, 1987; Battis, 1987 and Witten, 1988). Witten concluded the following statements from information obtained from these field studies concerning the hush house as an acoustic source: (1) low -frequency emissions peak in the 10 -15 Hz range, (2) these emissions behave as a near monopole source located at the rear of the hush

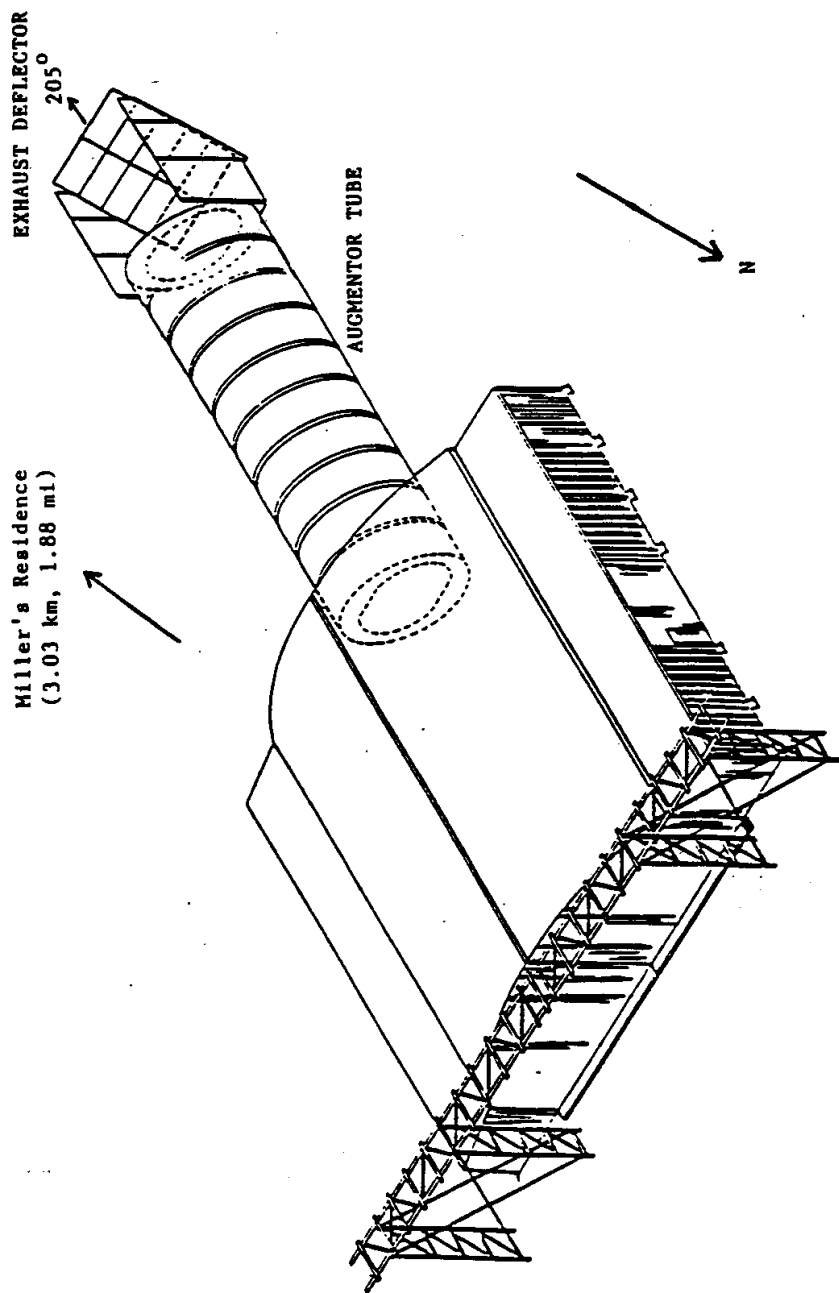


Figure 1. Sketch of a Langley AFH T-10 Hush House.

house, and (3) infrasonic emissions increase (in magnitude) substantially at higher engine power levels."

In addition to defining the acoustic source from the T -10 Hush House, the previous vibroacoustic field studies provided several models that can be used to predict vibroacoustic effects due to T -10 Hush House infrasonic emissions. Three of these models include a vibroacoustic response of structures model (Witten, 1988), an acoustic emissions model (Battis, 1987), and a vibroacoustic forecasting model (Battis, Crowley, 1986). These models were based on data obtained at distances less than 1,600 ft from their respective T -10 Hush House source. Since this report addresses the vibroacoustic effects on structures at distances greater than 9,500 ft from the hush house source, these models were not used for the prediction of vibroacoustic effects that were addressed by this field study.

Ellis and Schaffer (1989) performed a field noise survey at Langley AFB that addressed vibroacoustic effects on structures at distances greater than 9,500 ft. They found that vibroacoustic effects on the structures were caused from T -10 Hush House infrasonic emissions on Langley AFB. They also found that these vibroacoustic effects varied due to wind direction. The low frequency energy, they felt, was being channeled by the wind to create vibroacoustic problems downwind of the hush houses. This report further addresses the vibroacoustic effects on structures that were addressed by Ellis and Schaffer.

2.0 SITE DESCRIPTION

2.1 LOCATION

Langley AFB, Virginia, is located in the southeastern corner of the state at the juncture of the northwest and southwest branches of the Back River (Figure 2). The southwest branch of the Back River separates Langley AFB from Sherwood Park where homeowners are complaining about vibrations caused by T-10 Hush House emissions from Langley AFB.

Instrumentation for the surveys in this study were located in areas adjacent to the T -10 Hush Houses, in Eagle Park, and inside and adjacent to a civilian home in Sherwood Park (Miller's residence). The two T -10 Hush Houses are located on the north end of the main runway and are oriented so that their augmentor tubes emit jet engine exhaust on a 205 degree radial. Eagle Park is located approximately 5,400 ft (1.02 mi) on a 185 degree radial from the hush houses. The Miller's residence is located approximately 9,925 ft (1.88 mi) on a 180 degree radial from the hush houses.

2.2 TOPOGRAPHY/GEOLOGY

The topography of Langley AFB is very flat, showing little or no relief. The ground elevations range from 2 to 10 ft above N an sea level. The topography from the hush houses through Eagle Park across the Southwest Branch of the Back River to the Miller's residence is very flat. In addition, there are no man made or natural barriers along this radial to help attenuate acoustic energy from hush house emissions.

Surficial deposits occurring at Langley AFB and the Miller's residence consist of alluvial sediments, primarily sandy, silty clay or silty, clayey sand. The water table ranges in depth from 1 to 12 ft on Langley AFB and is at an approximate depth of 2 ft at the Miller's residence.

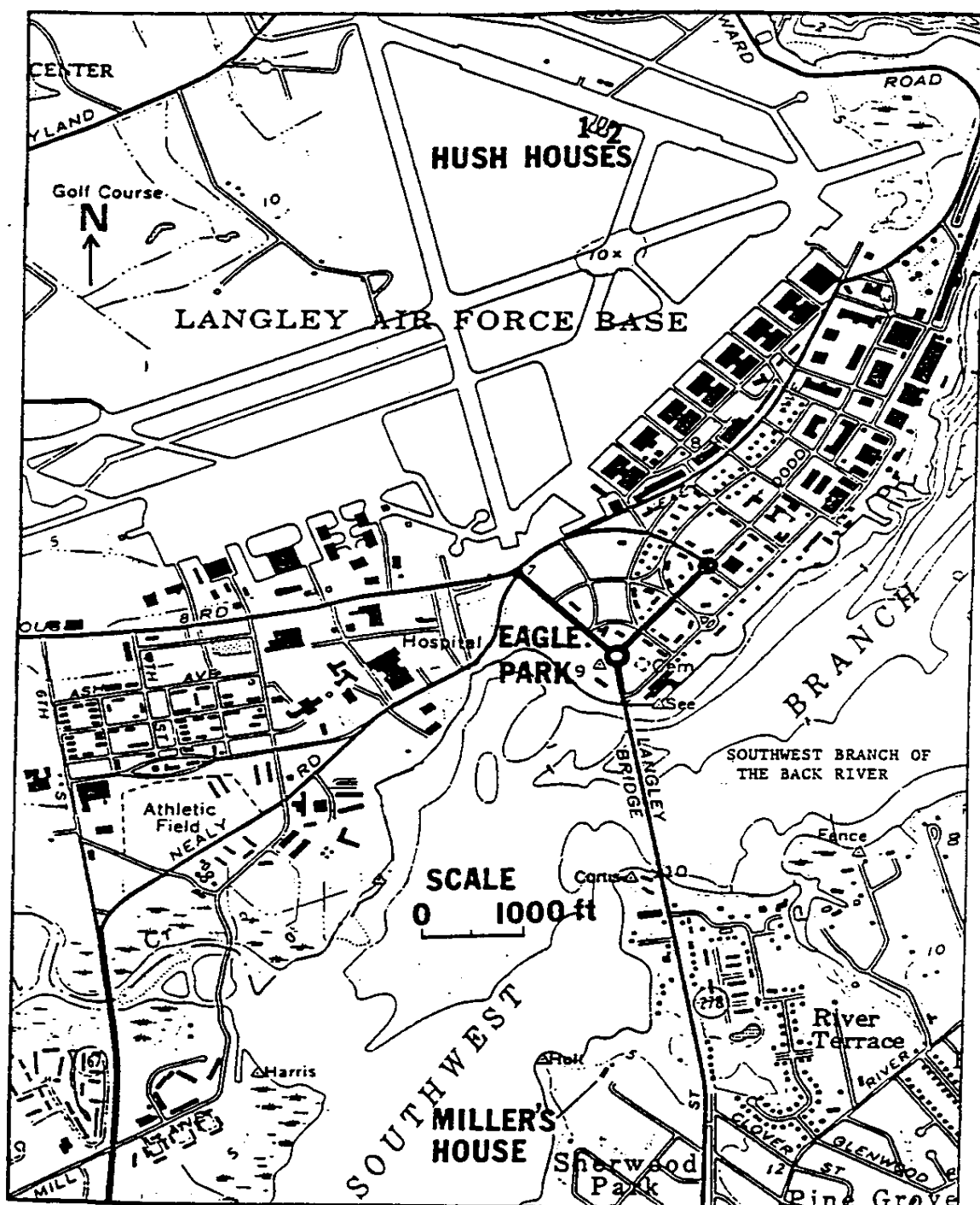


Figure 2. Map of study area.

3.0 PROCEDURE

3.1 METHODOLOGY

The WL performed twelve field surveys that included several different types of instrument configurations. Each survey was performed to gather acoustic overpressure and seismic data to answer specific questions concerning T-10 Hush House acoustic emissions and the resulting vibroacoustic effects on local structures. Overpressure and seismic measurements in this study were made when an F-100 engine and/or F-15 aircraft were operating on afterburner or military power in one of the two T-10 Hush Houses in Langley AFB. From the overpressure and seismic data obtained, the WL was able to answer several questions concerning the effects of weather (winds, inversion, etc.), topography, structural design, and geology on acoustic energy and seismic propagation from hush house emissions on Langley AFB.

Survey 1 (Figure 3) was performed to determine acoustic overpressure and seismic near-field (< 1000 ft) attenuation from hush house emissions. Data from survey 1 was also used with data from survey 7 to determine whether "engine only" (F-100 engine) operations provided more infrasonic emissions than installed engine (F-15 aircraft) operations.

Survey 2 (Figure 4) was performed to determine what the effects of wind are on hush house emissions and whether there is a directional component intrinsic to hush house emissions. In addition, data obtained from station 3 was used to determine the magnitude of the ground acceleration directly behind the exhaust deflector.

Survey 3-6, 8-11 & 7 (Figures 5 & 6, respectively) were performed to determine the vibroacoustic effects of T-10 Hush House emissions on the Miller's residence in variable weather conditions. In addition, data from these survey were used to model acoustic overpressure and seismic attenuation from hush house emission in the far-field. Figures 7-8 show the location of the instruments at the Miller's residence for surveys.

SURVEY 1 27 JAN 90 LANGLEY AFB

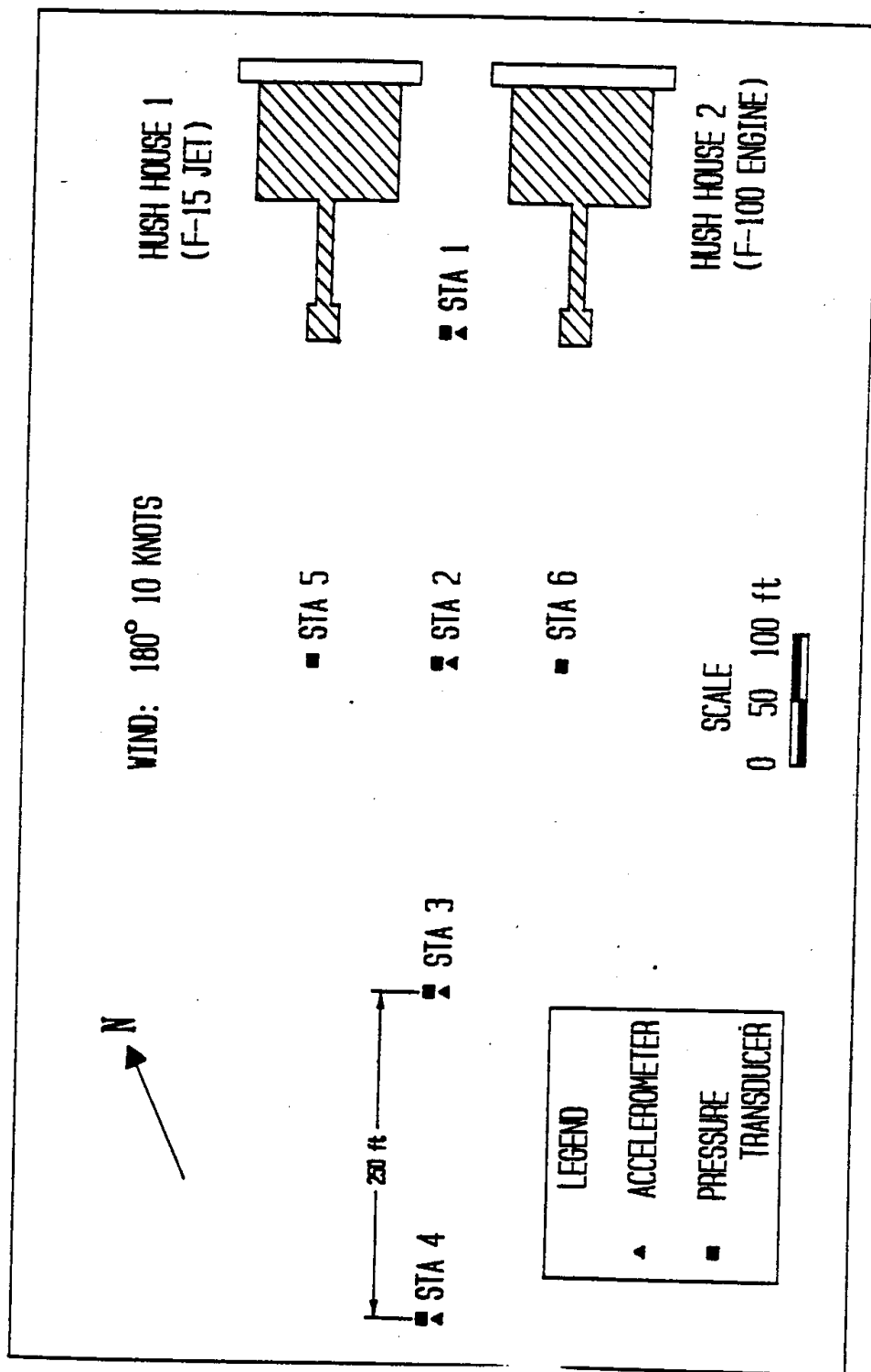


Figure 3. Instrumentation location (Survey 1).

SURVEY 2 27 JAN 90 LANGLEY AFB

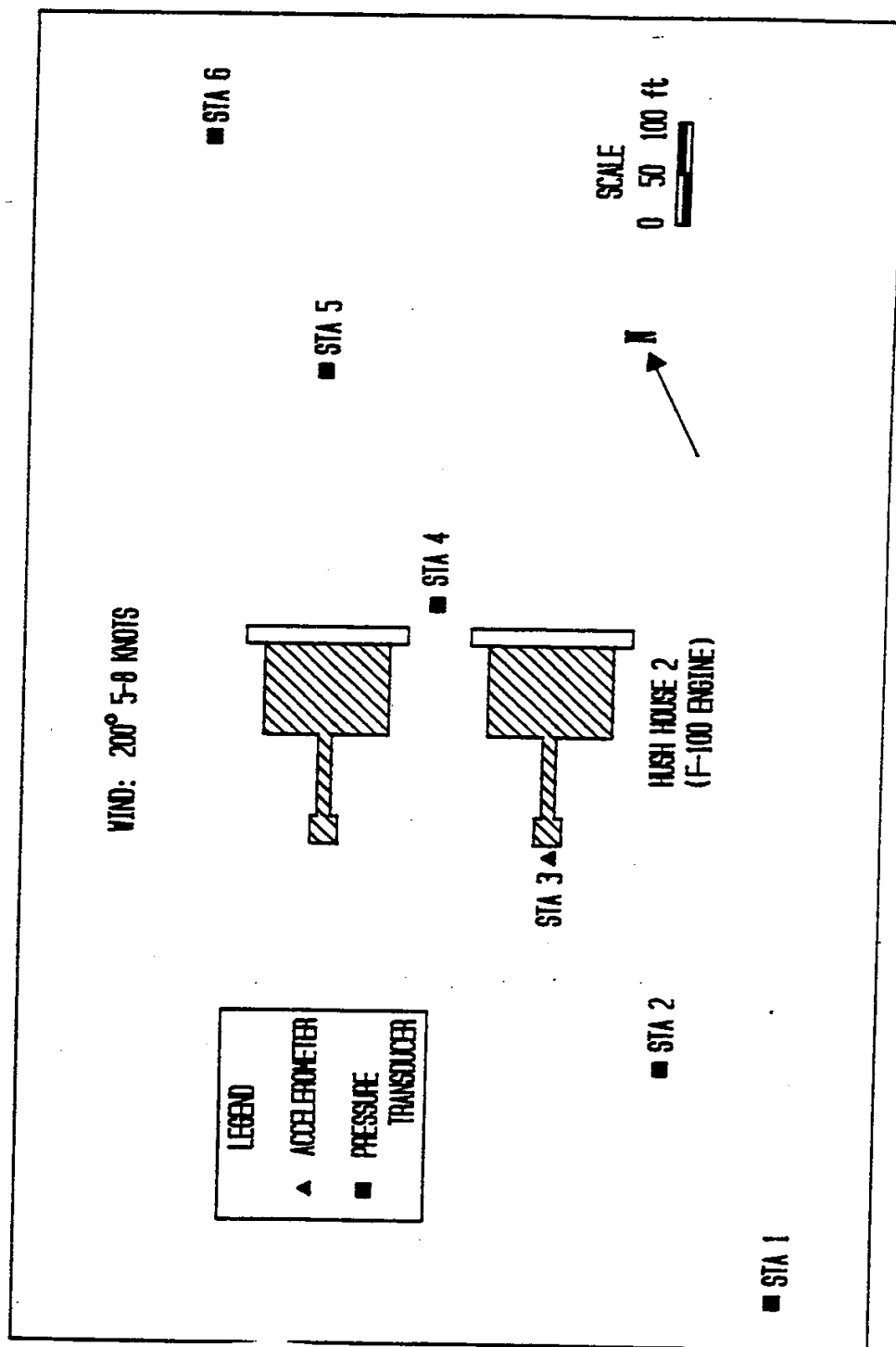


Figure 4. Instrumentation location (Survey 2).

SURVEYS 3-6, 8-11 29-31 JAN 90 LANGLEY AFB

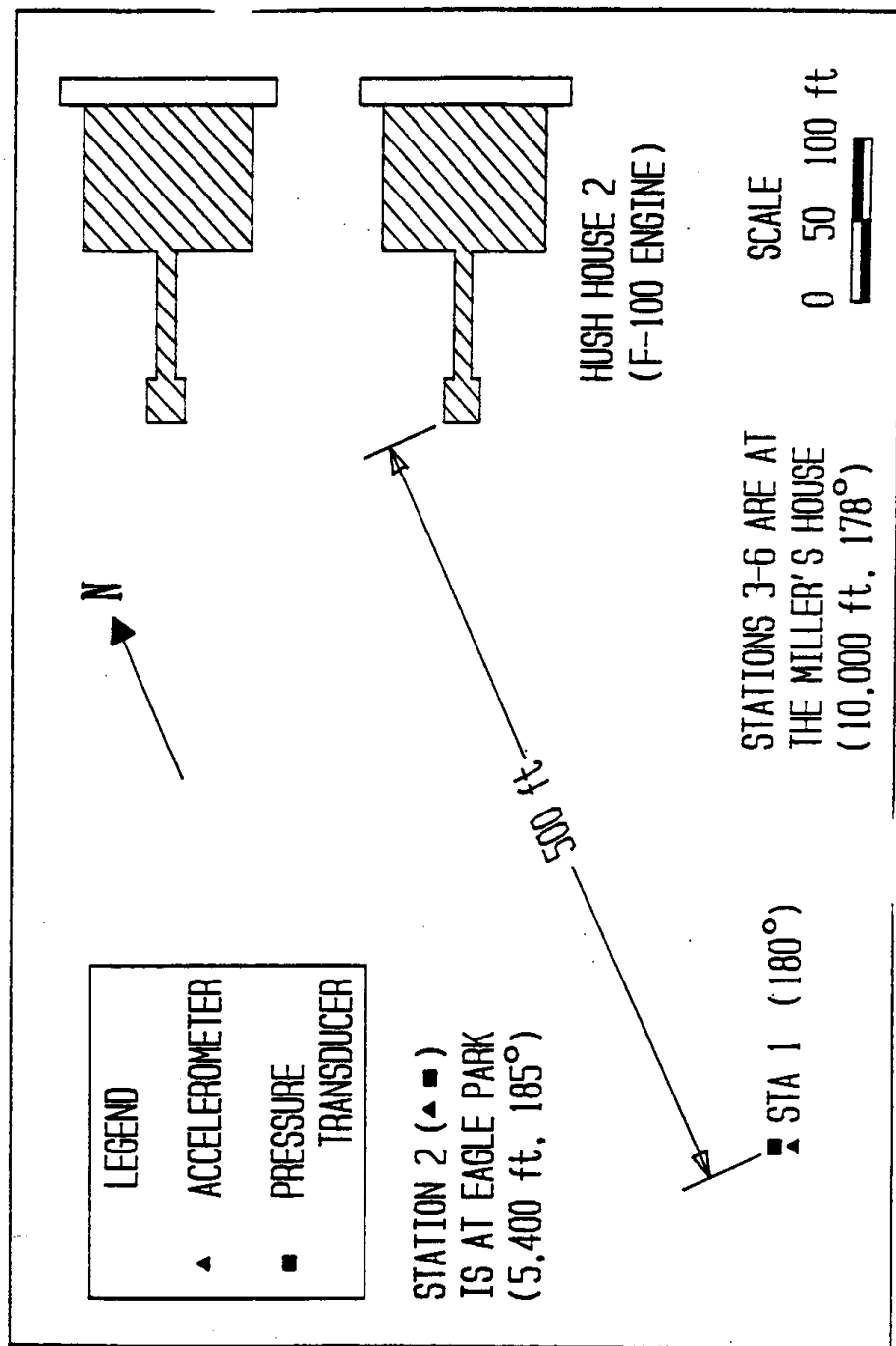


Figure 5. Instrumentation locations (Surveys 3-6 and 8-11).

SURVEY 7 30 JAN 90 LANGLEY AFB

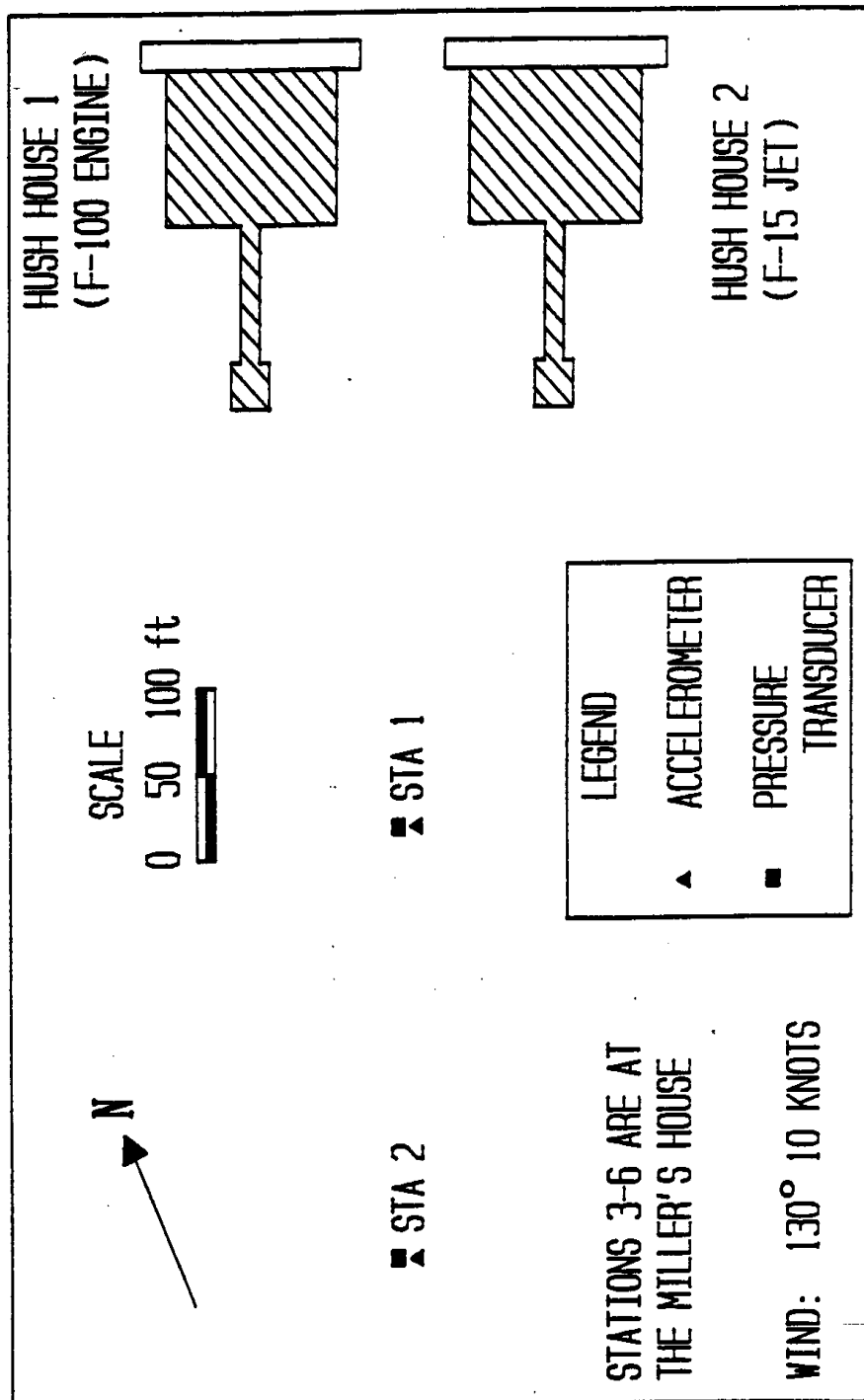


Figure 6. Instrument location (Survey 7).

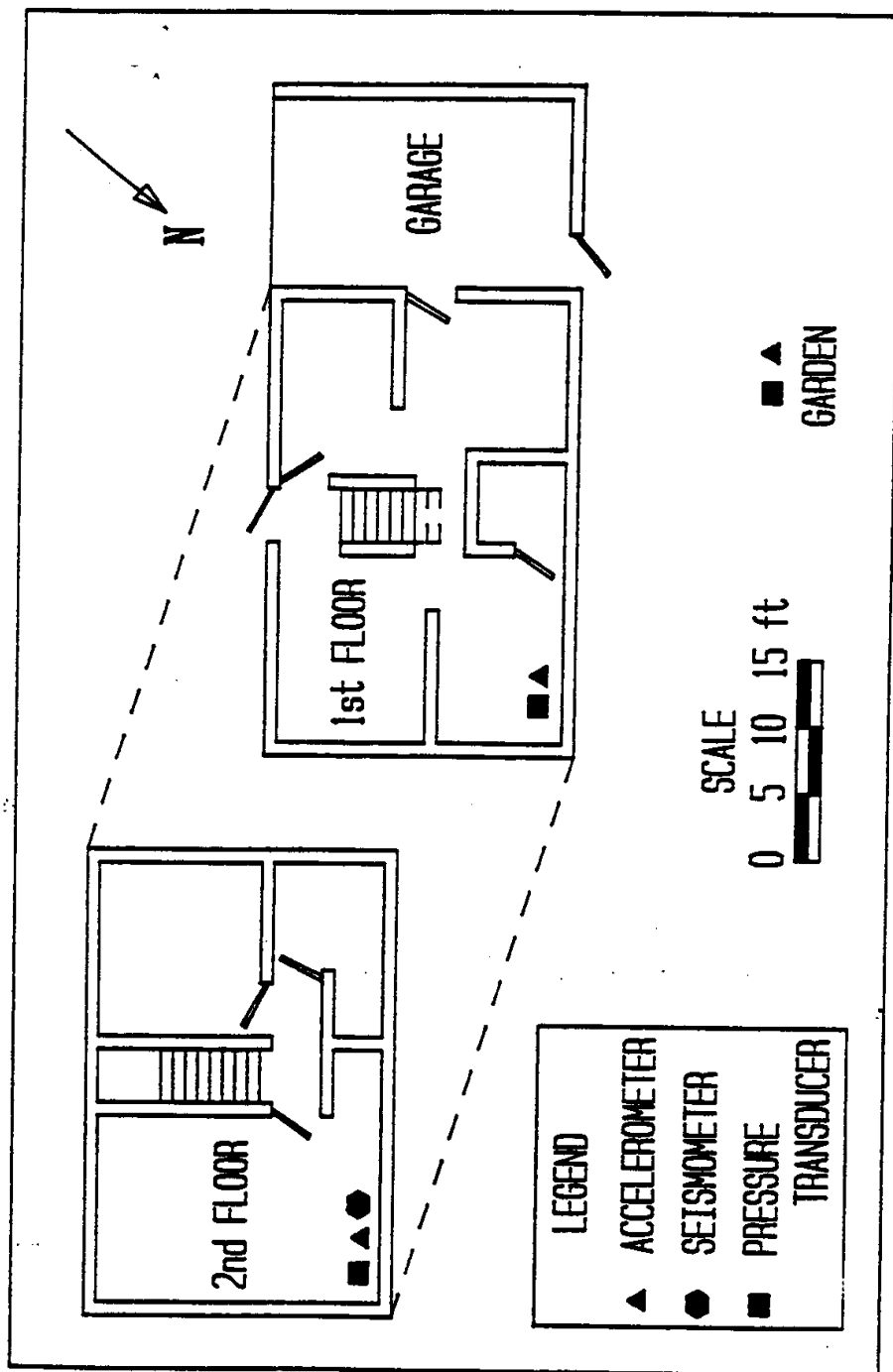


Figure 7. Instrumentation location at Miller's house (Surveys 10-11).

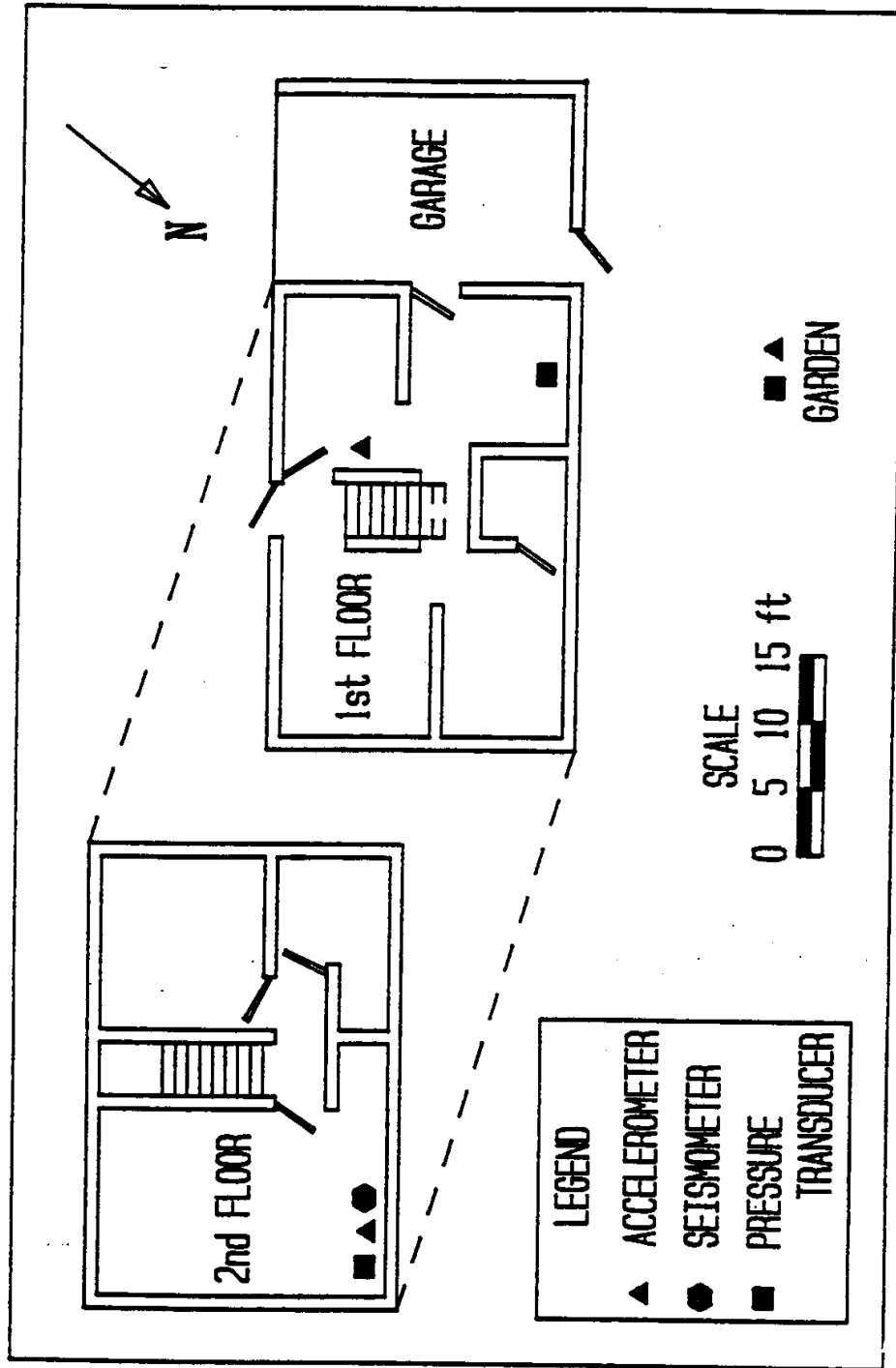


Figure 8. Instrumentation location at Miller's house (Surveys 3-9).

Weather conditions, including wind speed, and wind direction, were monitored for each survey by a meteorologist.

3.2 INSTRUMENTATION

The instrumentation used in the hush house surveys consisted of six portable digital recorders, six servo accelerometers, six low pressure transducers, and one velocity seismometer. The digital recorders were used to record the seismic and acoustic energy signals and to interface the signals with a PC for analysis.

The Terra Technology DCS -302 three channel digital recorder filters, amplifies, and digitizes sensor data in a 12 bit format and stores the digitized signals on magnetic cassette tapes. For surveys 1 -11 the DCS-302 recorders were configured with 70 Hz anti -alias filters, sampling rates of 200 samples per second and gains dependent on location and type of sensor. For survey 12, three of the recorder's configurations were set to 1-channel operation with 200 Hz anti -alias filter and 600 samples per second sampling rate. System response for the recorders is flat from the anti-alias filter frequency down to DC.

The Terra Technology SSA -302 Accelerometer is a triaxial unit that measures vertical, radial, and transverse acceleration in g's. The accelerometer's frequency response is flat to acceleration in the 0 -50 Hz range.

The Sprengnether S -6000 Seismometer is a triaxial unit that measures vertical, radial and transverse seismic velocity in cm/sec. It consists of a moving coil, fixed magnet velocity gauge and it has a sensitivity of 1.1 volts/cm/sec. The seismometer's frequency response is flat to velocity in the 2 -40 Hz range.

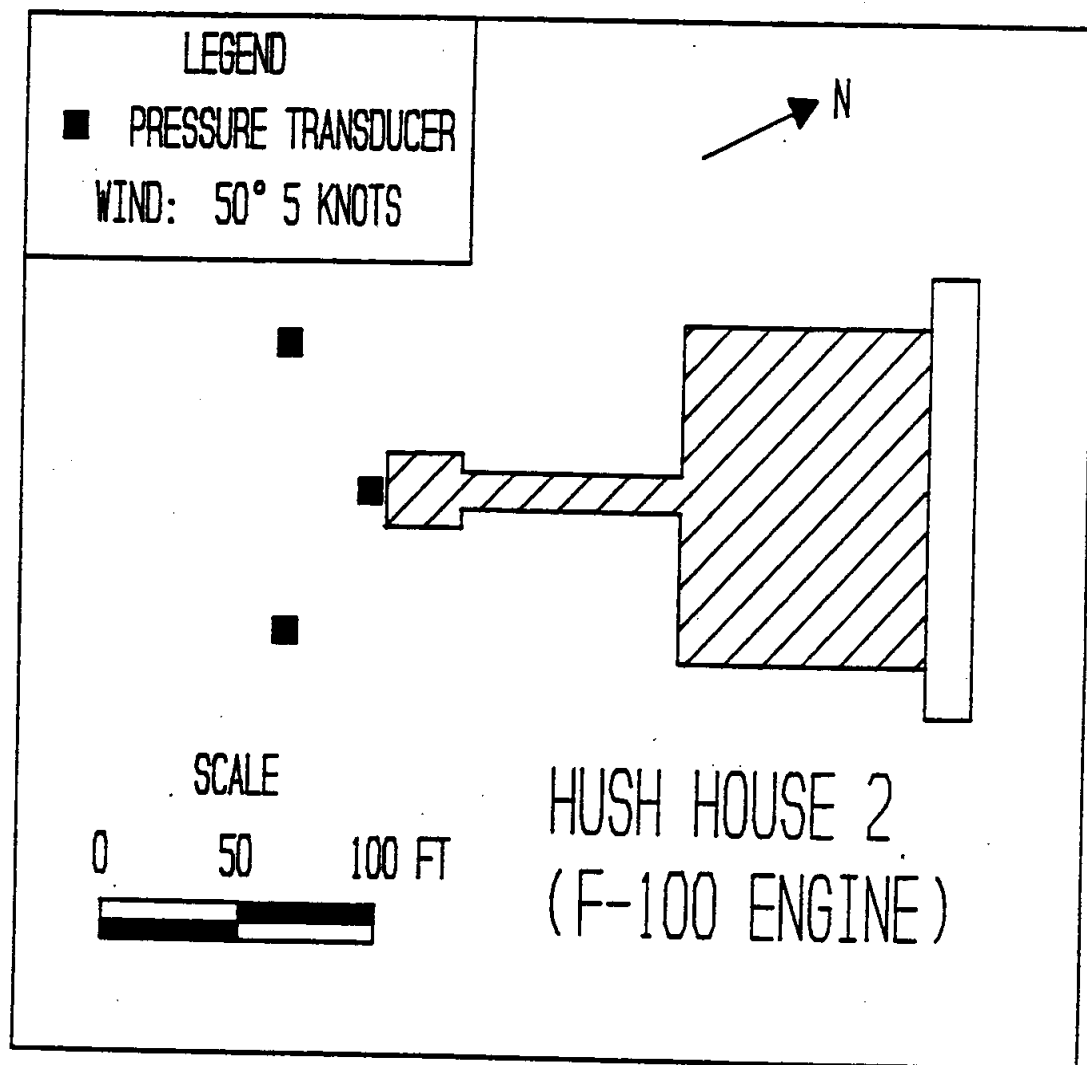


Figure 9. Intrumentation location (Survey 12).

The modified Validyne P305D Differential Pressure Transducer measures overpressure. IT consists of a variable reluctance transducer with a metal diaphragm to determine overpressure. The transducer's frequency response is flat from 0.1 to 200 Hz. The transducer has a range from 0 to 862 Pascals and it has a sensitivity of 0.0058 volts/Pascal.

4.0 TEST RESULTS AND DISCUSSION

4.1 SEISMIC MEASUREMENTS

Seismic measurements were made to answer the following questions concerning ground motion (acceleration and velocity) caused by T-10 Hush House operations at Langley AFB: (1) Is ground motion a significant contributor to the vibrations being felt at the Miller's residence? (2) How much of the ground motion is caused by air-coupling and how much is direct-induced? and (3) What role, if any, does the geology play in propagating ground motion caused by hush house operations?

(1) Is ground motion a significant contributor to the vibrations being felt at the Miller's residence?

Data obtained in this field study suggests that ground motion is not a significant contributor to the vibrations being felt at the Miller's residence. Figure 10 shows vertical acceleration at various distances away from Hush House 2 during surveys 1, 2, & 10. Hush House 2 had an F-100 engine running on afterburner during these surveys. The stations at Eagle Park, and the Miller's backyard recorded a maximum peak-to-peak vertical acceleration on survey 10 of 0.0003 g's and 0.00012 g's (Figures 11-12) respectively. Although the highest vertical accelerations were recorded on survey 10 inside the Miller's residence (Figure 13, .00075 g's in the Miller's upstairs bedroom), the vertical accelerations recorded at Eagle Park and in the Miller's backyard on survey 10 were imperceptible to humans and could not be a major contributor to the vibrations experienced inside the Miller's residence.

(2) How much of the ground motion is caused by air-coupling (acoustic energy-induced) and how much is direct-induced?

Prior to reviewing the data collected, it was thought that the shallow foundations used for both hush houses may have provided adequate coupled

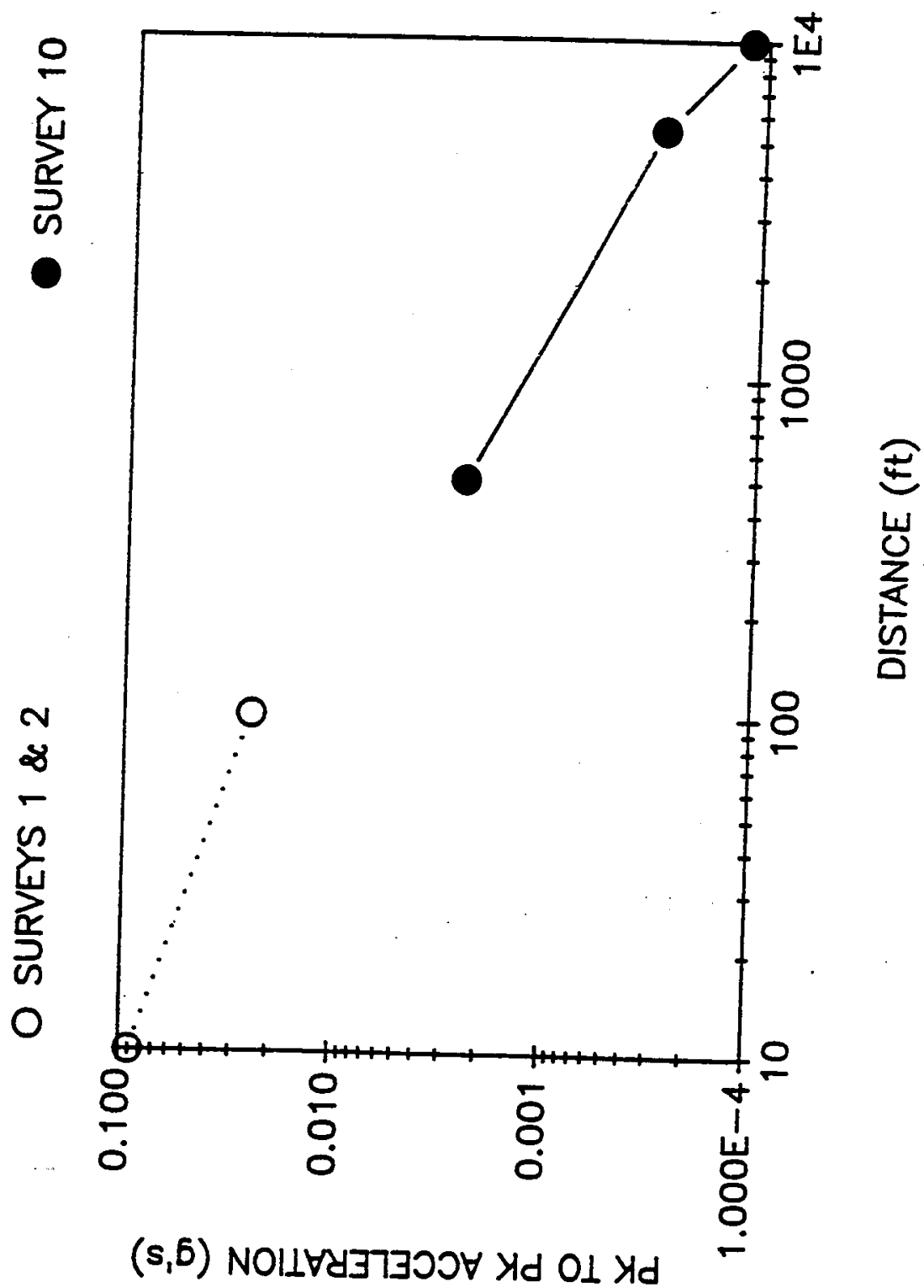


Figure 10. Measured vertical acceleration (Surveys 1, 2 and 10).

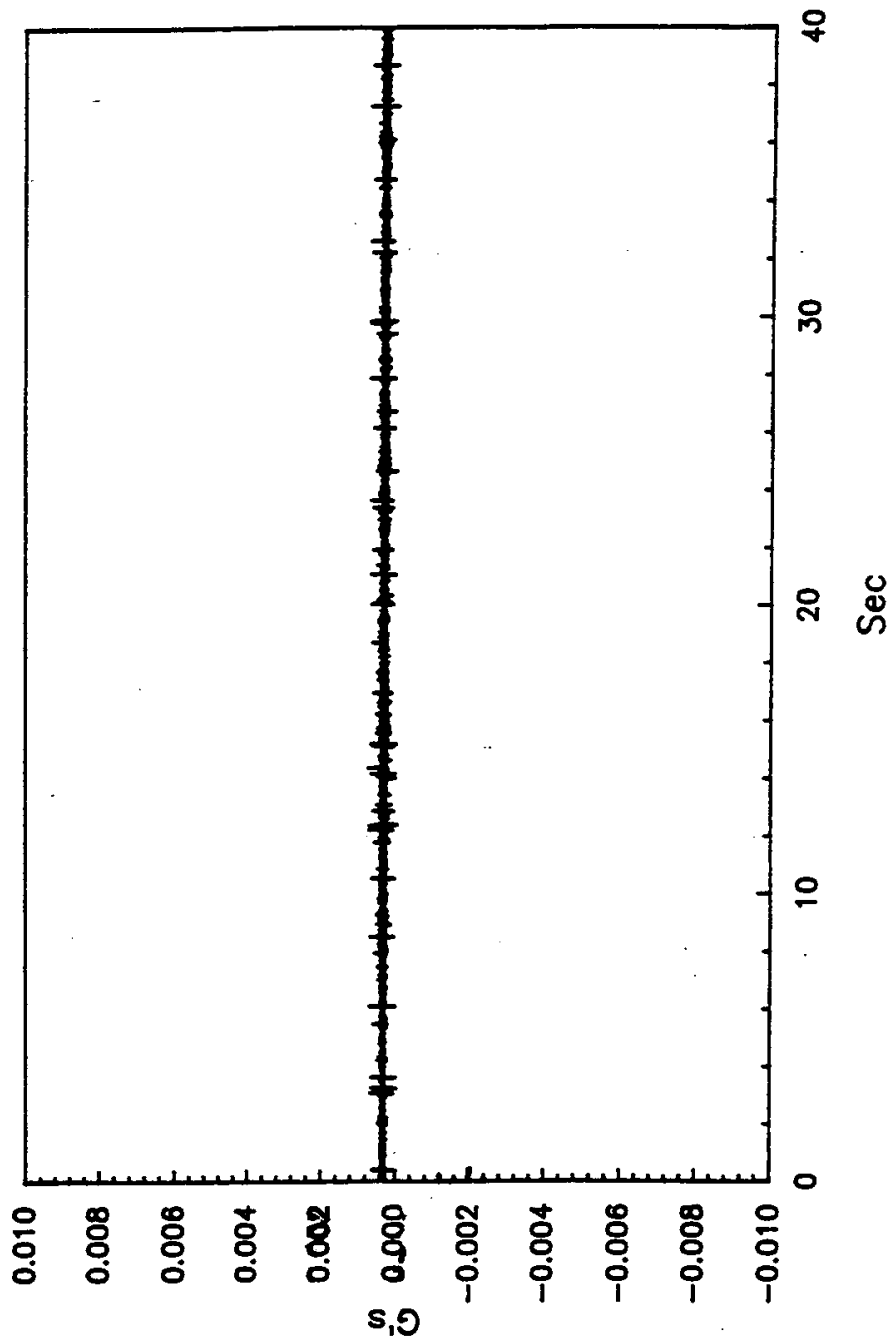


Figure 11. Measured vertical acceleration at Eagle Park (Survey 10).

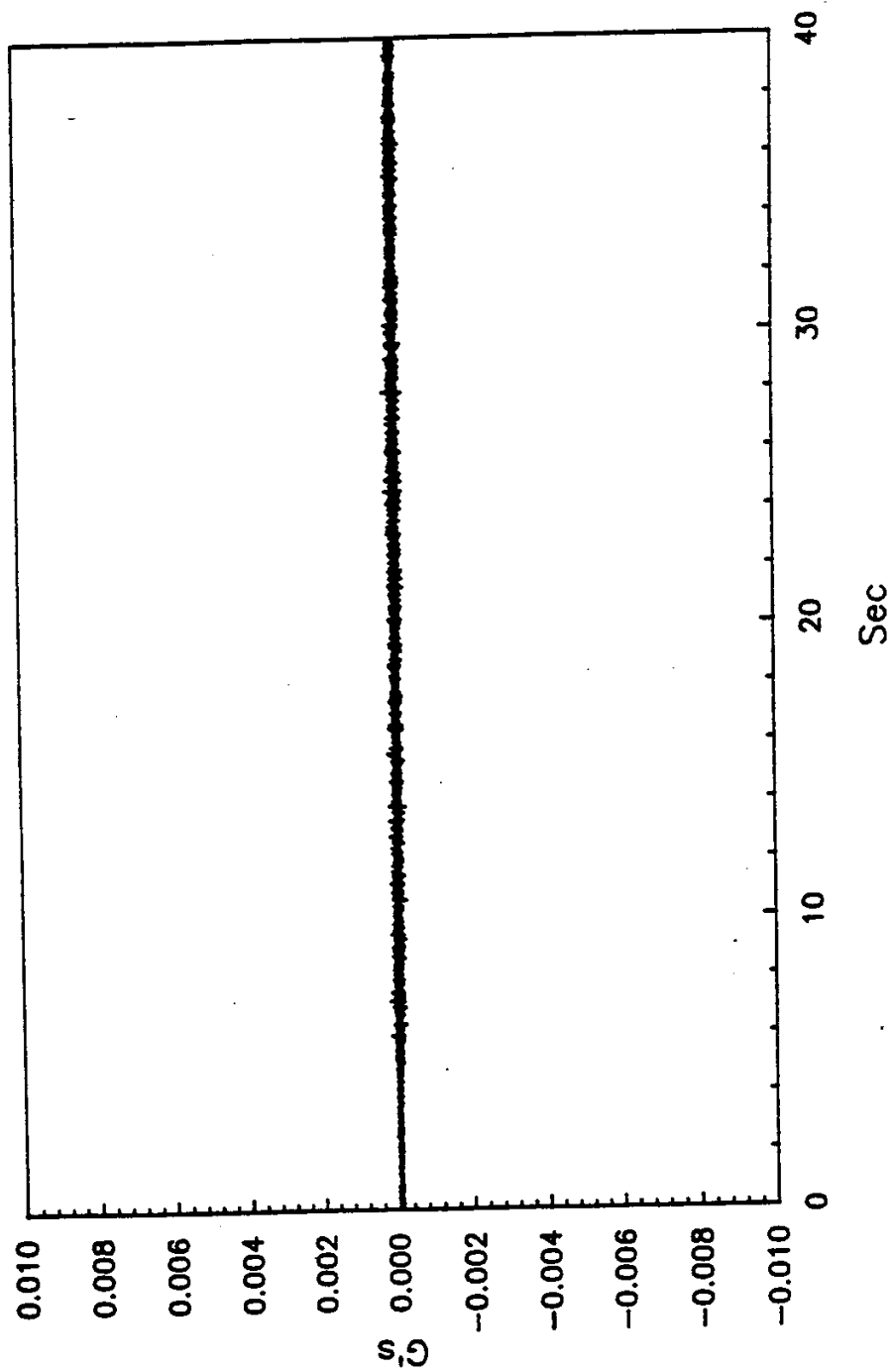


Figure 12. Measured vertical acceleration at Miller's backyard (Survey 10).

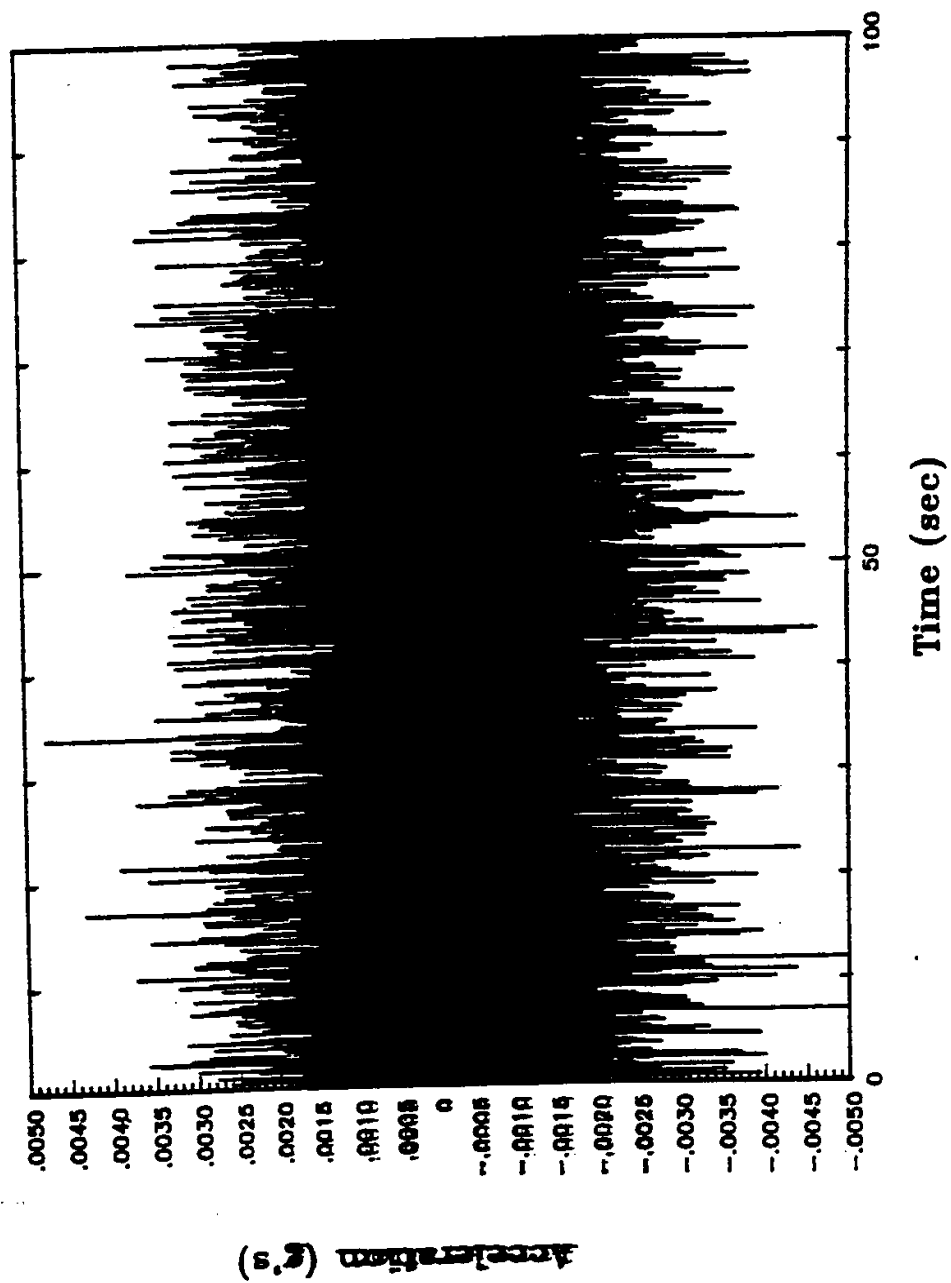


Figure 13. Measured vertical acceleration at Miller's house, upstairs
(Survey 10).

energy (direct -induced) into Langley AFB's saturated sandy clayey soil to be a major contributor to ground motions at far -field distances. From data obtained in this field study, it can be deduced that at far -field distances (> 5000 ft) the ground motion was primarily caused by air -coupling. At Eagle Park and in the Miller's backyard, no ground motion was measured when measured overpressures were less than 3 Pascals. However, on survey 10 (when the highest overpressures were measured) the ground acceleration measured at Eagle Park was 0.0003 g's and at the Miller's backyard the measured ground acceleration was 0.00012 g's.

At ranges less than 250 ft from the two hush houses' exhaust deflectors, ground accelerations that could potentially cause damage to structures were recorded during this study (vertical acceleration > 0.01 g's). Since the source (F-100 engine) requires a run -up, it was not possible to measure the time-of-arrival of the ground motion waves to determine how much of the measured ground motion was air -coupled or direct -induced. However, Beaupre and Crowley (1987) found in their field study at Luke AFB, that at all ranges, air -coupling provided the major impetus for ground motion. They concluded that since the T-10 Hush House provided an acoustic (atmospheric) source, the source strength and the specific acoustic impedance of the air-ground boundary control seismic intensity.

(3) What role, if any, does the geology play in propagating ground motion caused by hush house operations?

Since ground motion is not a significant contributor to the vibrations in the Miller's residence, the geology does not affect the propagation of ground motion at far -field distances. However, as mentioned previously, at ranges less than 250 ft from the two hush houses' exhaust deflectors, we recorded ground accelerations that could potentially cause damage to structures (vertical acceleration from 0.1 to 0.01 g's). Ground accelerations in this range may be harmful to structures and are dependent on geology. Beaupre and Crowley (1987) cite the following concerning the geological effects on ground motion: "The frequency for coupling acoustics

and seismics is a site dependent quantity. It is determined by the material constants of the ground, its layering and the phase velocity of the load. If topsoils near the hush house exhaust deflector have material constants that promote excitation when coupled with acoustic energy that has a predominant frequency in the infrasonic range, a low frequency air -coupled Rayleigh wave could occur that has a peak -to-peak acceleration an order of magnitude higher than other direct and air -coupled waves. Since the Rayleigh waves have higher amplitudes at low frequencies, they are more hazardous to structures than other seismic waves. These low frequency waves when coupled with structures produce larger particle displacement than higher frequency waves with the same amplitude. Geology, especially in the near field, could affect the propagation of ground motion caused by the air-coupling of infrasonic emissions from a T -10 Hush House.

4.2 ACOUSTIC OVERPRESSURE MEASUREMENTS

Acoustic overpressure measurements were made to answer several questions about the propagation of infrasonic emissions from T -10 Hush Houses. These questions and their answers are listed below:

1. Do T-10 Hush House emissions have a directional component in the radial direction of the exhaust flow through the augmentor tube?

The engine exhaust gas exits the T -10 Hush House through the augmentor tube. The augmentor tube, which is 79 ft long and oval in -cross-section, terminates at a 45 deg exhaust deflector which imparts a vertical component to the exhaust flow. Beaupre and Crowley (1987) concluded that, 'The exhaust flow (Figure 1) off the exhaust deflector cannot be modeled as a vertical annular jet, for unlike a jet, the hush house source spectra clearly depend on azimuth.'

Survey 2 (Figure 4) was performed to determine whether there is a directional component intrinsic to hush house emissions, and if there is, what is its azimuth (radial direction). The data obtained on survey 2 shows that, at least at close range, the overpressures will be larger in the exhaust flow radial direction (south to southwest) than in other directions, even when the wind is from the south to southwest. Figure 14 displays peak-to -peak differential overpressure versus distance for stations north and south of Hush House 2 during 'engine only' afterburner operation. The overpressures measured on survey 2 south of Hush House 2 are larger than the overpressures measured north of the hush house. Some of this difference may be attributed to the interference of the hush house structure to acoustic overpressure flow to the north. However, we believe that the majority of the difference is due to an intrinsic directional flow of T -10 Hush House emissions in the radial direction of the exhaust flow through the augmentor tube. Although more research should be conducted to support this theory, we believe that the directional components of Langley AFB's T -10 Hush House

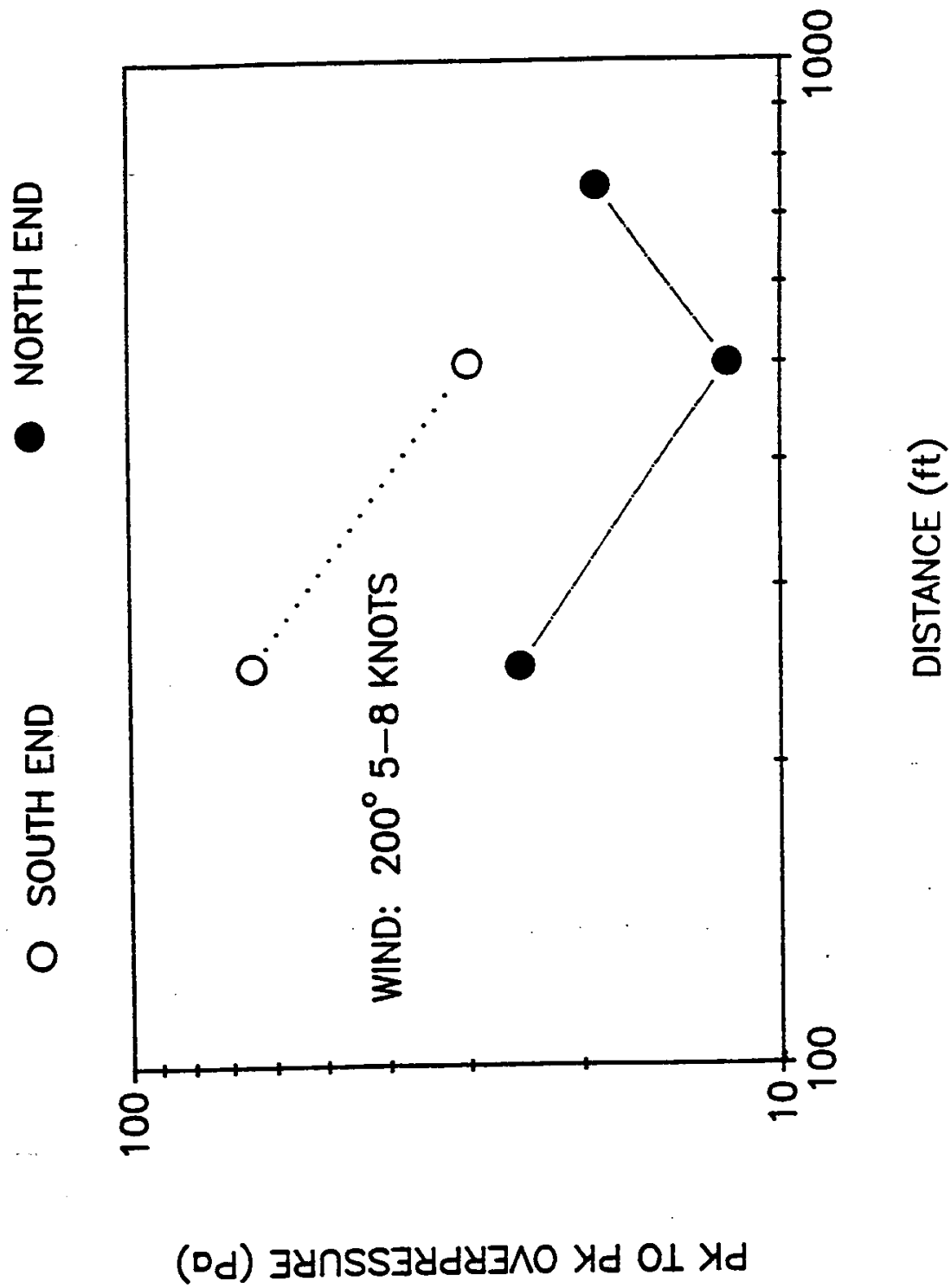


Figure 14. Measured overpressures north & south of Hush House 2 (Survey 2).

emissions to contribute to the higher than normal overpressure readings recorded in the Miller's backyard.

2. Does an uninstalled F -100 engine produce more infrasonic emissions than an installed F -100 engine (F -15 aircraft) while running on afterburner in a T -10 Hush House?

Ellis and Schaffer (1989) concluded that uninstalled engines produce more noise than installed engines during testing in Langley AFB's T -10 Hush House. Survey 1 (Figure 3) was performed to test Ellis and Schaffer's theory, and to determine if this theory could also be applied to infrasonic acoustic emissions. The data obtained on survey 1 (Figure 15) does support this theory. Peak -to-peak overpressures measured at various distances during uninstalled F -100 engine (engine only) testing were larger than those measured during installed engine testing. This dominance becomes even more apparent at farther distances (750 ft, amplitude of 16-18 Pa vs 9 Pa for the F -15).

To determine whether the difference in measured overpressures was due entirely to source (engine only vs F -15) differences, a survey had to be conducted to determine the effect the transmitters (hush houses) had on emissions. Could the differences in overpressure at distance be partially attributed to the acoustic attenuation differences between Langley AFB's two hush houses? Survey 7 was performed with the uninstalled engine in Hush House 1 and a F -15 in Hush House 2 (opposite of survey 1) to answer this question. Overpressures measured at a distance of 250 ft from the hush houses on survey 7 (Figures 16 -17) show a peak -to-peak amplitude of 75 Pa for engine only. afterburner testing and 65 Pa for F -15 afterburner testing. Since the measured differential overpressure was larger during "engine only" testing on both surveys, we believe that the uninstalled F-100 engine does produce more infrasonic emissions than an installed F-100 engine (F -15 aircraft) while running on afterburner in a T -10 Hush House. A probable explanation for this difference is that the F -15 structure acts as a tamper to infrasonic emissions from the F -100 engine.

○ BOTH ● F-100 ENGINE ONLY △ F-15 ONLY

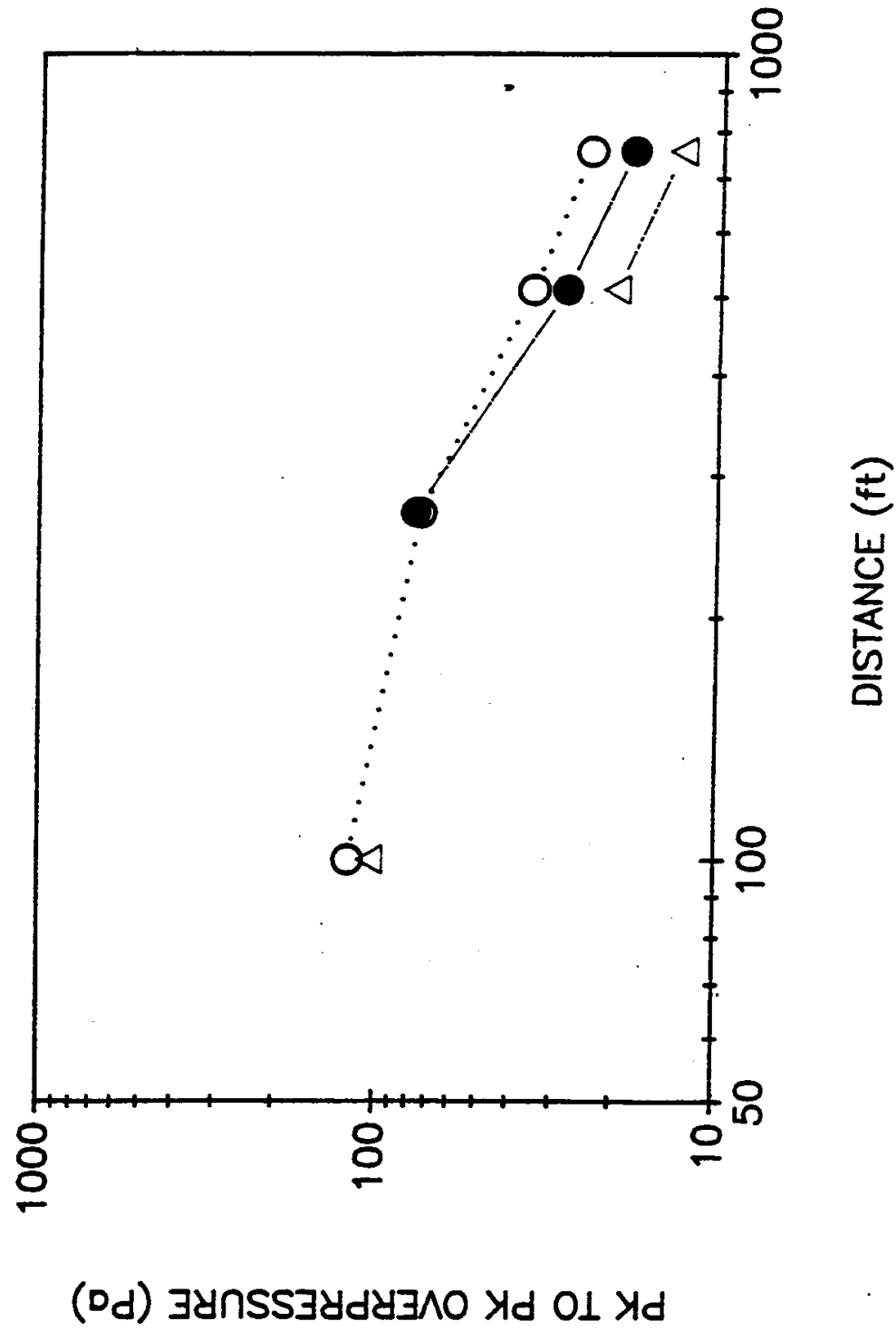


Figure 15. Measured overpressures during afterburner testing (Survey 1).

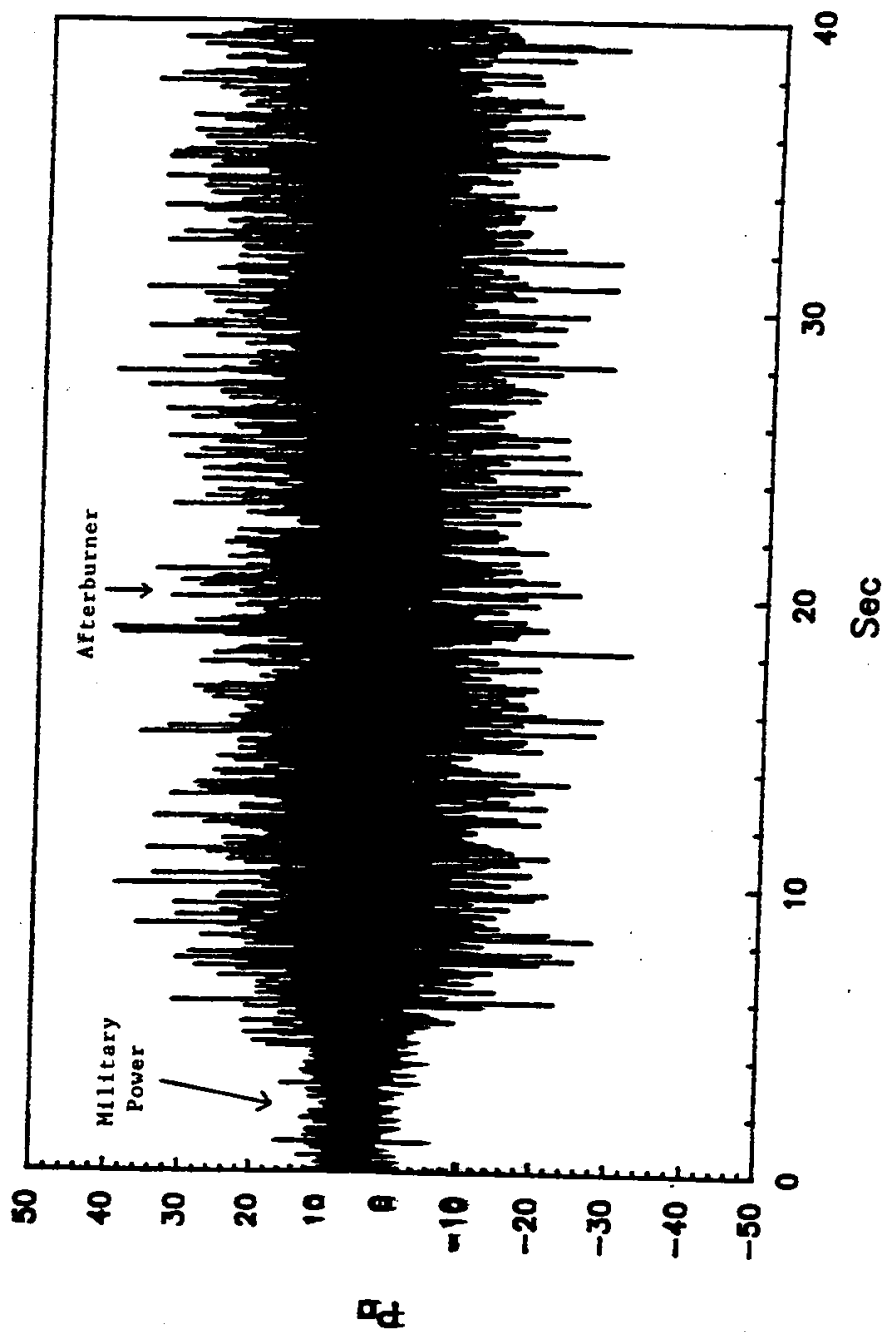


Figure 16. Measured overpressures for engine only testing at a station 250 ft south of exhaust exit (Survey 7).

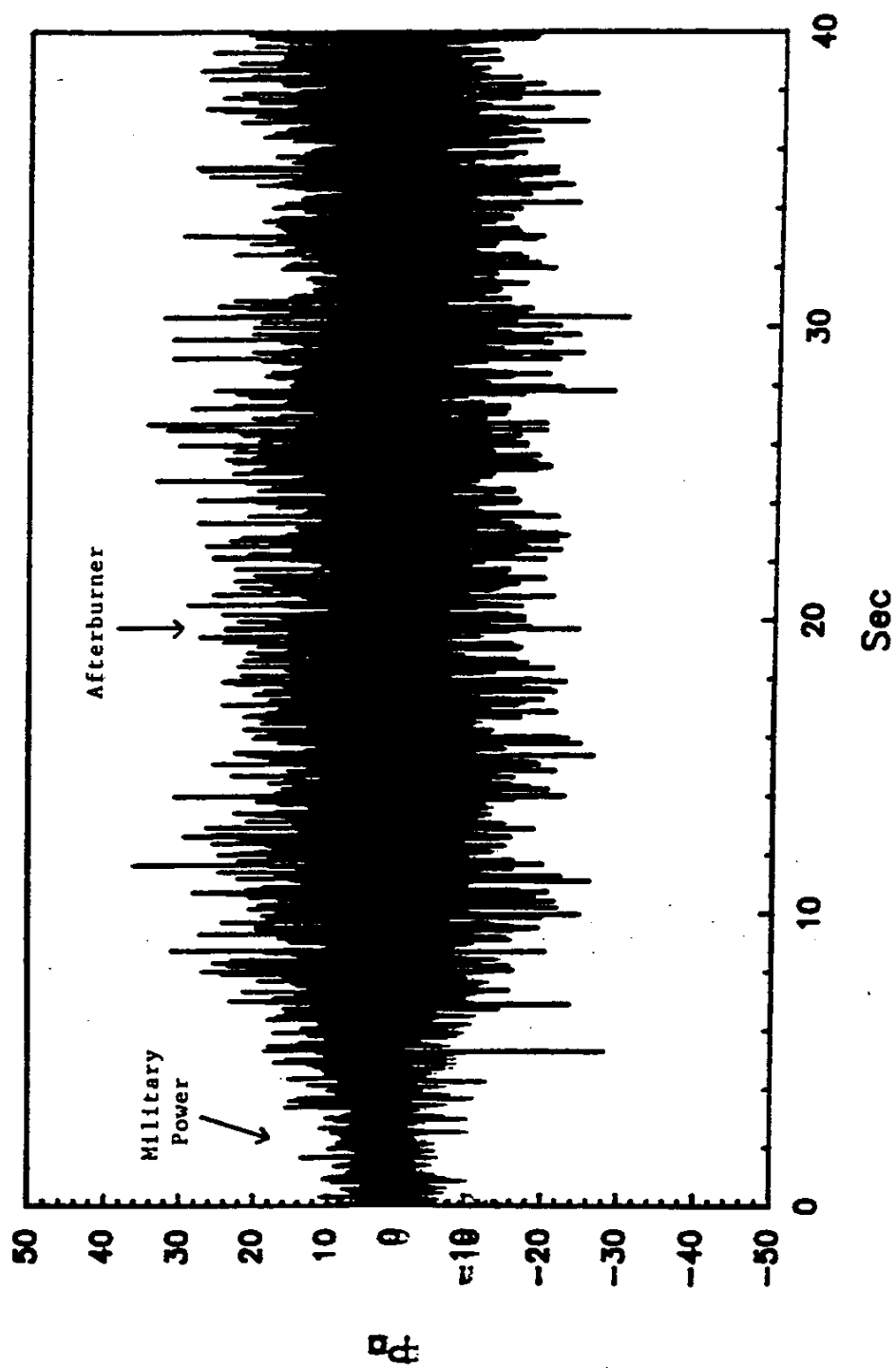


Figure 17. Measured overpressures for F-15 testing at a station 250 ft south of exhaust exit (Survey 7).

3. How do the infrasonic emissions attenuate over distance from the hush house, and do the higher frequency emissions attenuate faster than the low frequency emissions?

Beaupre and Crowley (1987) found that for distances less than 750 ft from a T-10 hush House at Luke AFB, attenuation decreases with increasing frequency. Near -field overpressure data obtained in this study supports their theory. The predominant frequency directly behind the exhaust deflector was 8 to 15 Hz (Figure 18), at a station 100 ft west of the exhaust deflector it was 10 to 18 Hz (Figure 19), and at a station 500 ft south of the exhaust deflector it was 20 to 30 Hz (Figure 20).

Far-field overpressure data obtained in this study do not support this theory. At far -field distances, the predominant frequencies began dropping , thus showing attenuation increases with increasing frequency. The predominant frequency in the Miller's backyard (1.88 miles away) was 15 to 25 Hz (Figure 21). The predominant frequency dropped even more inside the Miller's residence (12 to 16 Hz, Figure 22), showing the ability of the low frequency acoustic energy to permeate through structures.

This permeation of low frequency acoustic energy through structures presents a possible theory for the rise and then fall of predominant frequencies with distance from the exhaust deflector. At very close distances to the exhaust deflector, the overpressures measured contain primarily low frequency energy that permeates through the panel. As the distance from the exhaust deflector increases, the higher frequency acoustic energy that was deflected over the panel gradually mixes in with the low frequency acoustic energy. Mixing will be completed at a distance from the exhaust deflector that would be strongly dependent on atmospheric conditions. Under this theory, you'd expect a rise in frequency with range until the deflected acoustic energy has completely mixed in; then a gradual decrease in frequency with range will occur as the higher frequencies attenuate faster than the lower frequencies. Another survey that includes more radial data points followed by spatial attenuation of the data would be needed to prove this theory.

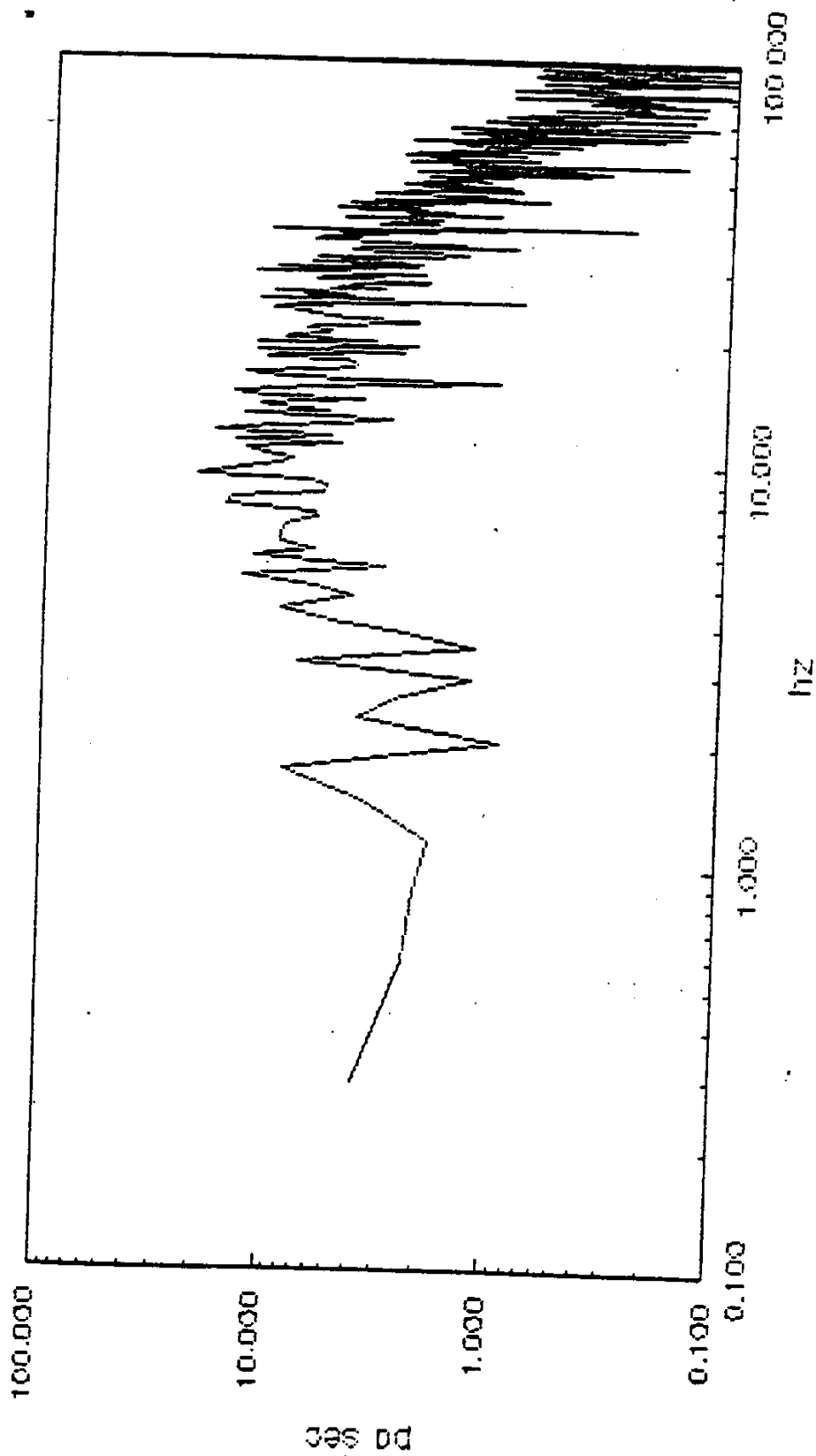


Figure 18. FFT frequency plot for station at 2 ft in front of exhaust exit (Survey 12).

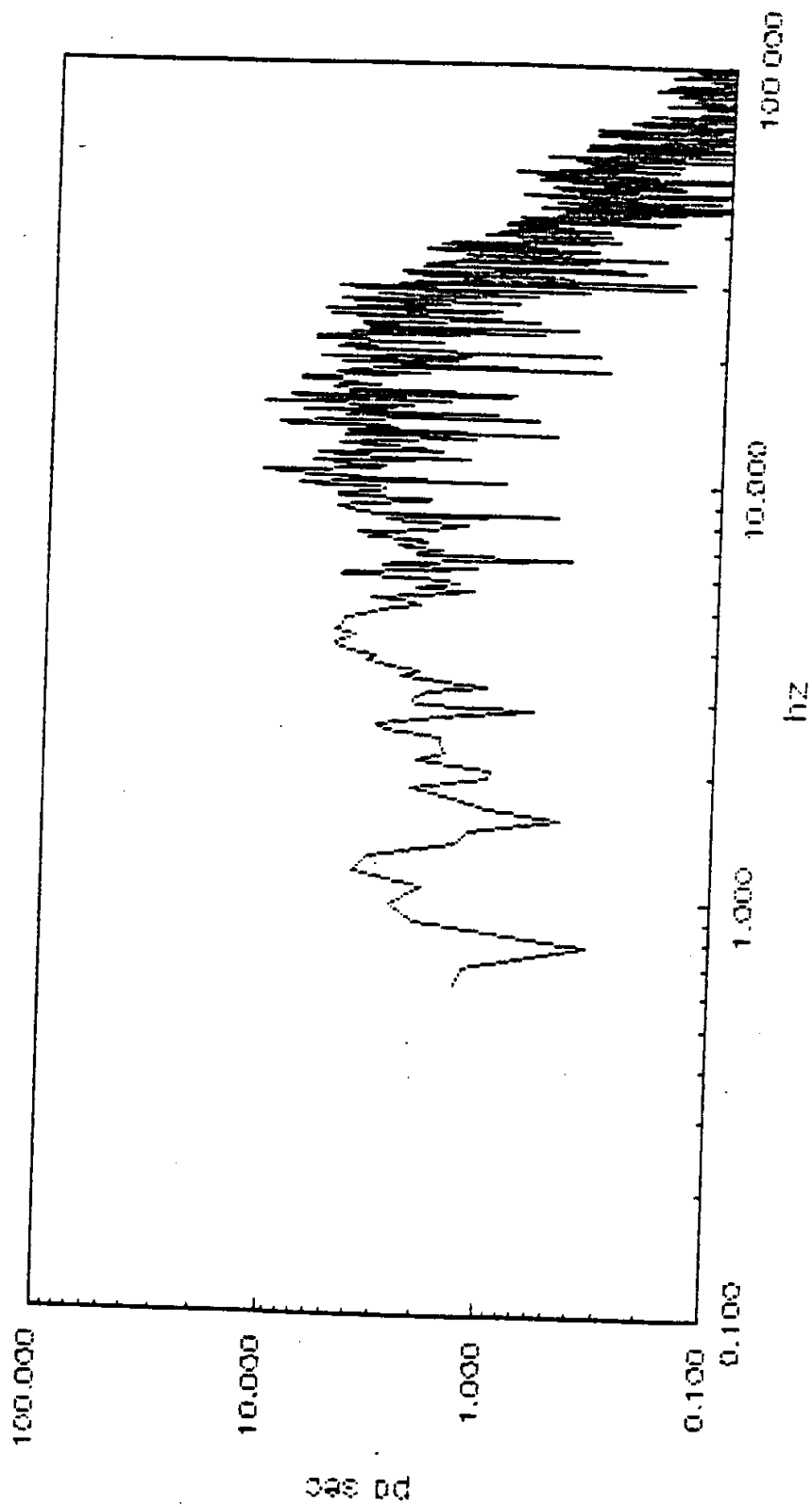


Figure 19. FFT frequency plot for station 1 at 100 ft west of exhaust exit (Survey 1).

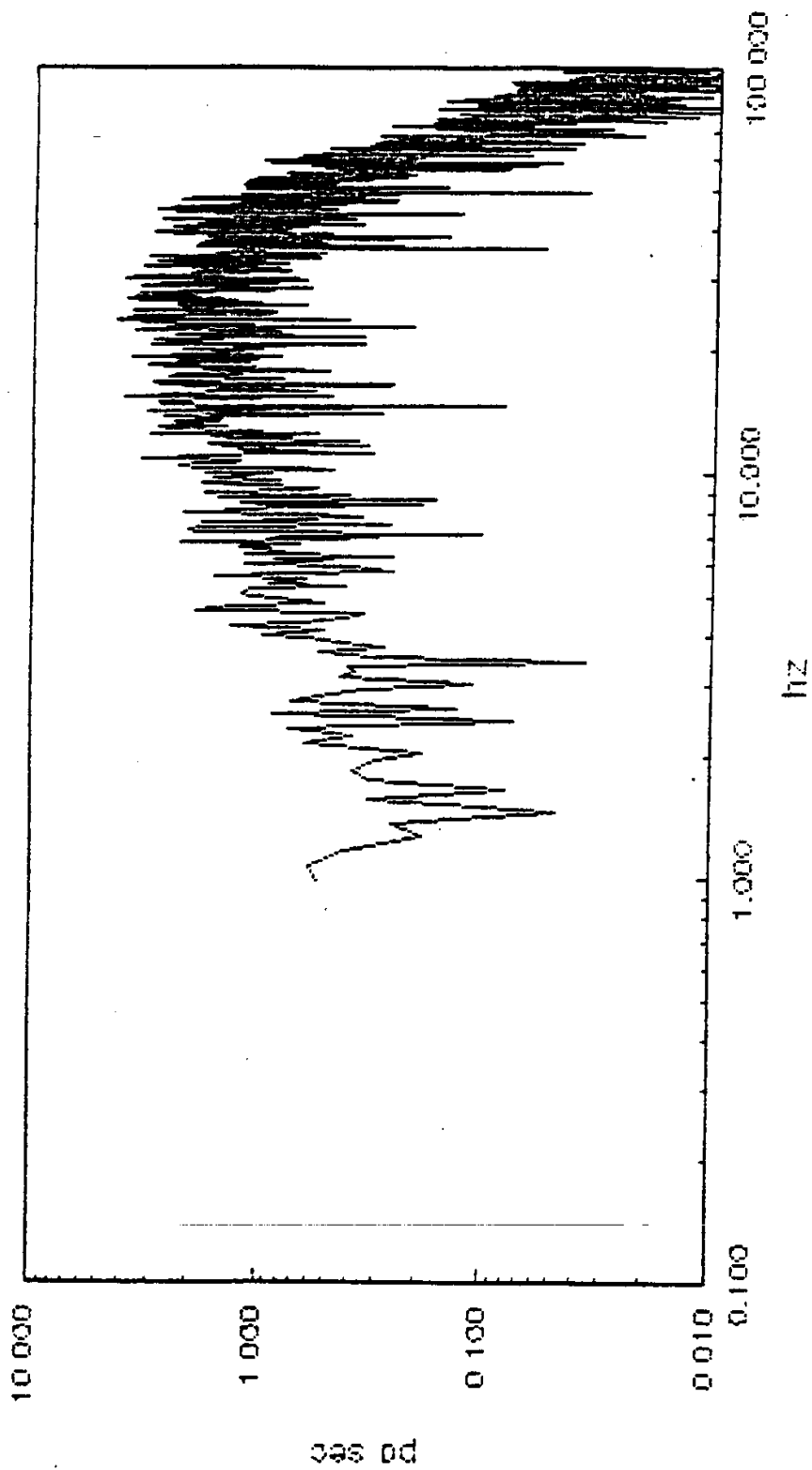


Figure 20. FFT frequency plot for station 1 at 500 ft south of exhaust exit
(Survey 10).

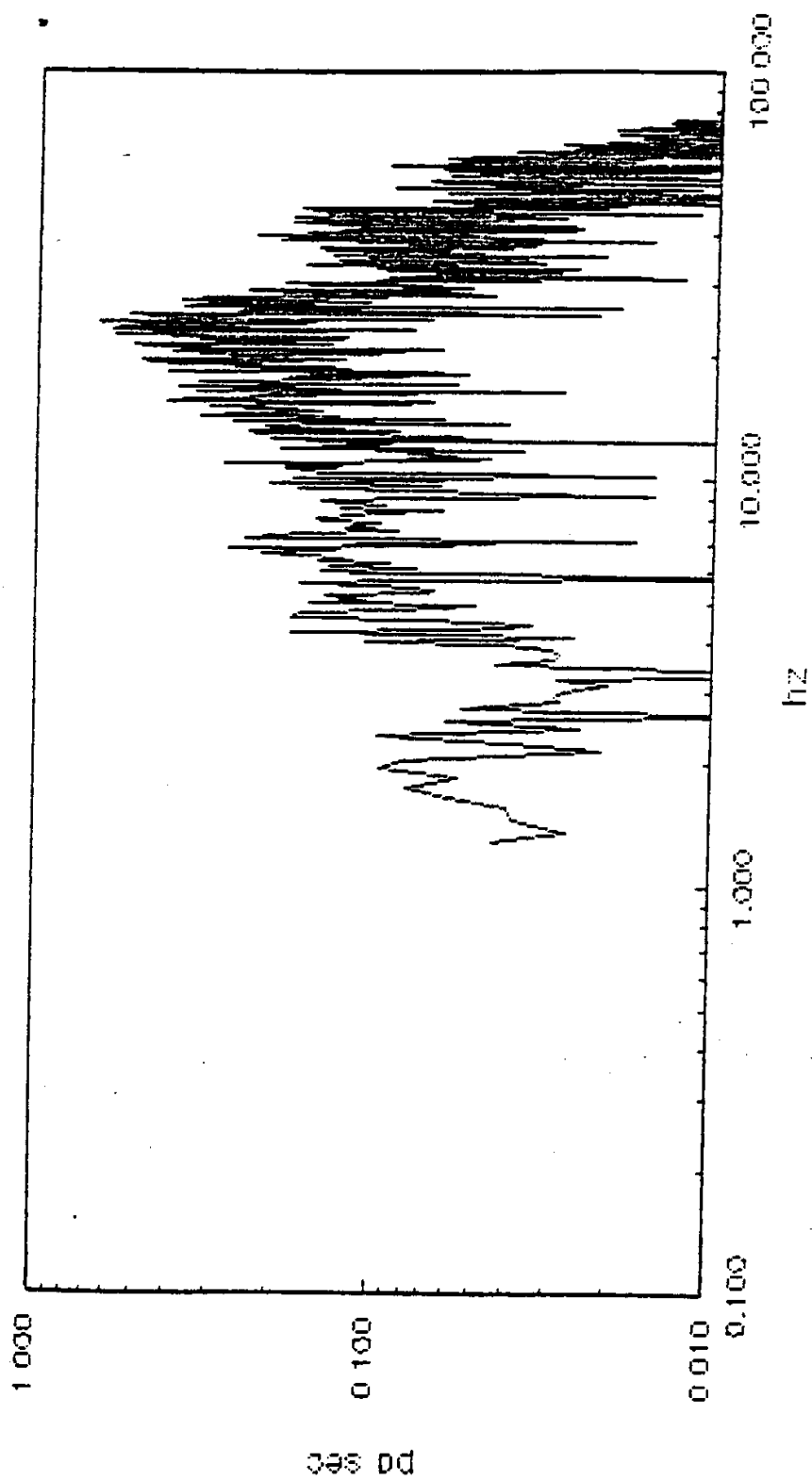


Figure 21. FFT frequency plot for station 6 at Miller's backyard (Survey 10).

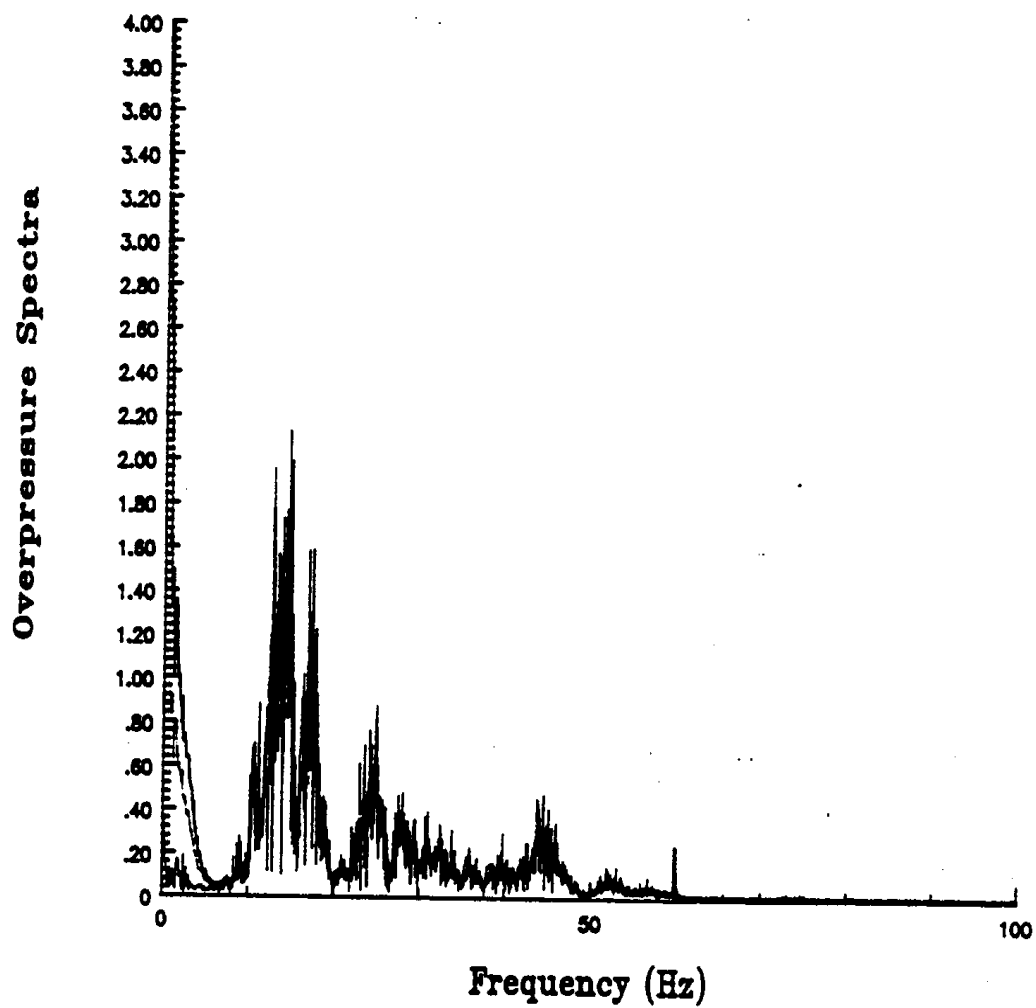


Figure 22. Overpressure spectra at Miller's house, upstairs (Survey 10)..

4. How much of the infrasonic emissions from the T -10 Hush Houses on Langley AFB go through the exhaust deflector rather than go over? Would a select fill berm located behind the exhaust deflector help attenuate the infrasonic emissions that escape through the exhaust deflector?

As the engine exhaust exits the T -10 Hush House through the augmentor tube, it impacts a 45 degree exhaust deflector. The majority of the engine exhaust (emissions) gets deflected over this panel. However, based on observation and measurement, a considerable amount of the emissions permeate through the exhaust deflector. A peak -to-peak overpressure of 560 Pascals with a predominant frequency of 8 to 15 Hz was measured directly behind the panel on survey 12. This was the higher overpressure and lowest predominant frequency measured in this study.

Witten (1988) suggested that acoustic Cherenkov Radiation, which originates in the high speed portion of the engine exhaust flow, is the cause for the hush house's infrasonic emissions. "Acoustic Cherenkov radiation," according to Witten, "is similar to a shock wave and occurs when a hot gas is moving faster than the speed of sound in the surrounding air. n As suggested in the previous section, we believe that the overpressure measured directly behind the exhaust deflector consist mostly of the Cherenkov radiation (infrasonic emissions) that permeate through the exhaust deflector.

The original design drawings for T -10 Hush Houses ca}led for select fi ll behind the exhaust deflector and an earth berm fully covering the three exposed sides of the structure at the end of the augmentor tube (the exhaust deflector side and the two concrete retaining walls). The fill and berm were taken off of the original design for Langley AFB's T -10 Hush Houses and were subsequently deleted from the design for all future T -10 Hush Houses for maintenance purposes. The effect that this decision had on high frequency noise was addressed, and it was found not to be a problem. The effect on infrasonic emissions, however, was not addressed. Personal communication with Dr. Alan Witten of the Oak Ridge National Laboratory and

Mr. Art Woytek of the AFLC/SA -ALC explain why the fill and berm solution was not addressed:

A. It] is felt that most all of the hush house's acoustic emissions are deflected over the exhaust deflector and, therefore, would not be affected by a berm.

B. The whereabouts of the original hush house designer is unknown, his calculations/theory were either lost or never obtained, and no one knows why the fill and berm were put in the original design.

C. The fill and berm solution probably would not attenuate infrasound because the infrasound's wavelength is about twice as long as the length of the augmentor tube (158 ft). The acoustic energy would easily travel through the berm unless the berm is extremely thick.

The relevant facts that lead us to believe that the fill and berm may attenuate some of the infrasonic emissions that reach the Miller's residence are:

A. A significant amount of the acoustic energy does permeate through the exhaust deflector (560 Pascals at 10 ft behind the exhaust deflector).

B. The predominant frequency of the acoustic energy permeating through the exhaust deflector is infrasonic (8 -15 Hz).

C. The predominant frequency of the acoustic overpressure measured on survey 10 in the Miller's backyard is also infrasonic (15 to 20 Hz).

D. Calculations from analyses performed (see "Residential Structure") on the Miller's residence gave natural frequencies of the two response modes of 8 Hz and 20 Hz. Acoustic energy of sufficient amplitude with an infrasonic predominant frequency in the 8 to 20 Hz range would resonate this structure.

E. Medearis (1979) stated that soil typically has natural frequencies less than 20 Hz. Since soil has a low natural frequency, according to Ristvet (1990), a berm that is composed of high porosity soil (sand or pea gravel) located directly behind the exhaust deflector would attenuate some of the low frequency energy that permeates through the exhaust deflector by converting the acoustic energy into friction energy.

Although, the aforementioned facts point to the fill and berm as an inexpensive solution; it is entirely possible that the scenario described is unrealistic. The exhaust deflector may detect most all of the acoustic energy from the bush house emissions; and it is this overpressure that is entirely responsible for the vibrations at the Hiller's residence. However, we believe that even if a minute amount of the energy that does permeate through the exhaust deflector reaches the Hiller's residence, the fill and berm may provide enough acoustic attenuation to warrant its use along with the primary solution (i.e. turning vanes, etc.).

5. How do atmospheric conditions effect the infrasonic emissions from the T-10 Hush House? Are refracted infrasonic acoustics from T -10 Hush House infrasonic emissions the cause of the vibrations at the Hiller's residence and the other civilian homes in Sherwood Park?

Based on data obtained in this study, we believe that low -level temperature inversions and surface wind ducts are two mechanisms that refract the acoustic energy from Langley AFB's two T -10 Hush Houses toward the Miller residence. A third possible refracting mechanisms, suggested by Ristvet (1990), is a density gradient cawed b7 a continuous low level cloud layer. This mechanism could not be substantiated by data obtained in this study, and, therefore, will not be addressed in this paper.

Data listed on Table 1 and displayed on Figures 23 -25 illustrate the effects of atmospheric conditions on the refraction of the hush house acoustic emissions and the resulting acoustic overpressures at the Hiller's residence. In all three cases listed, an uninstalled F -100 engine was fired

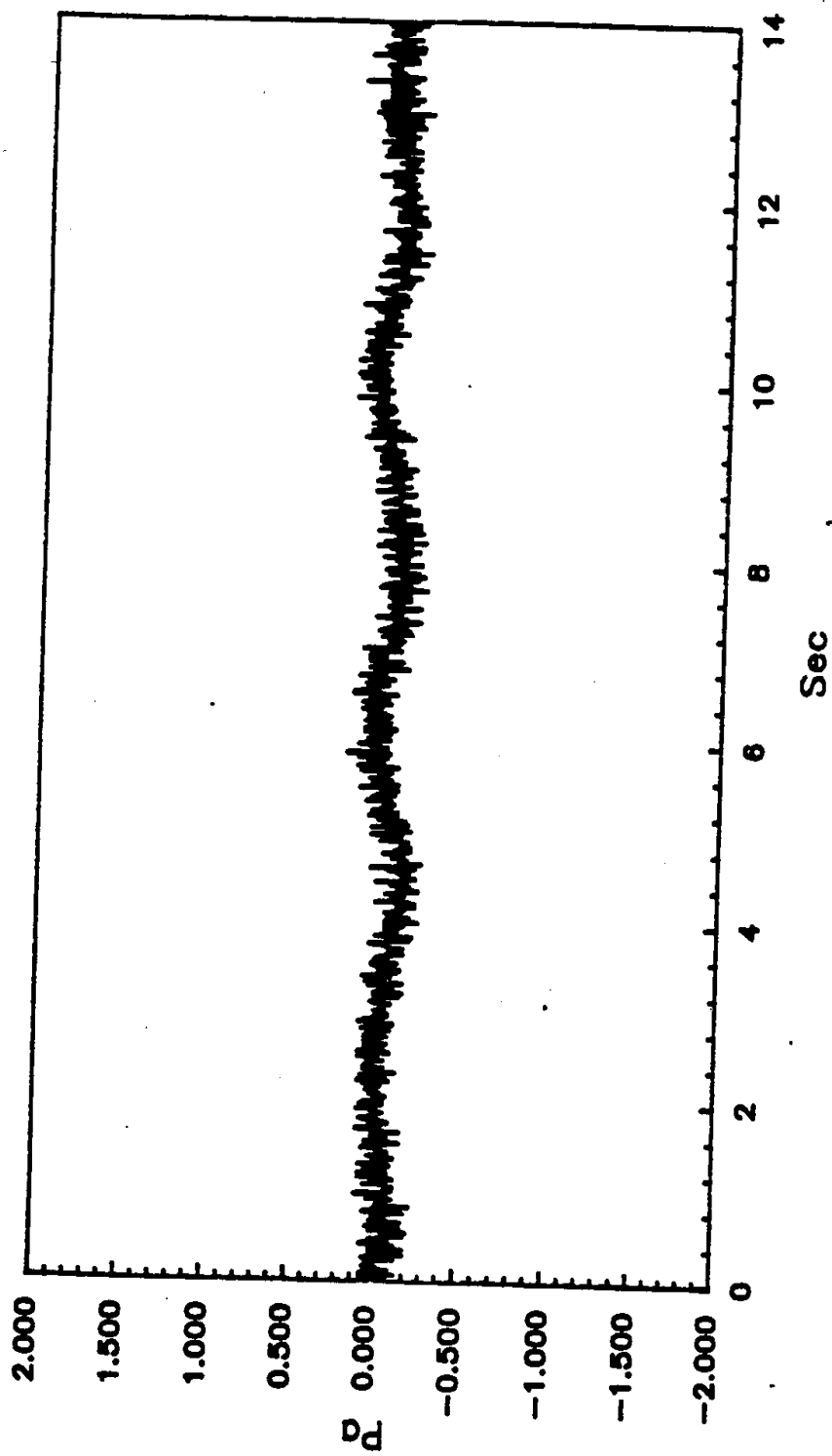


Figure 23. Measured overpressure at Miller's backyard (Survey 7).

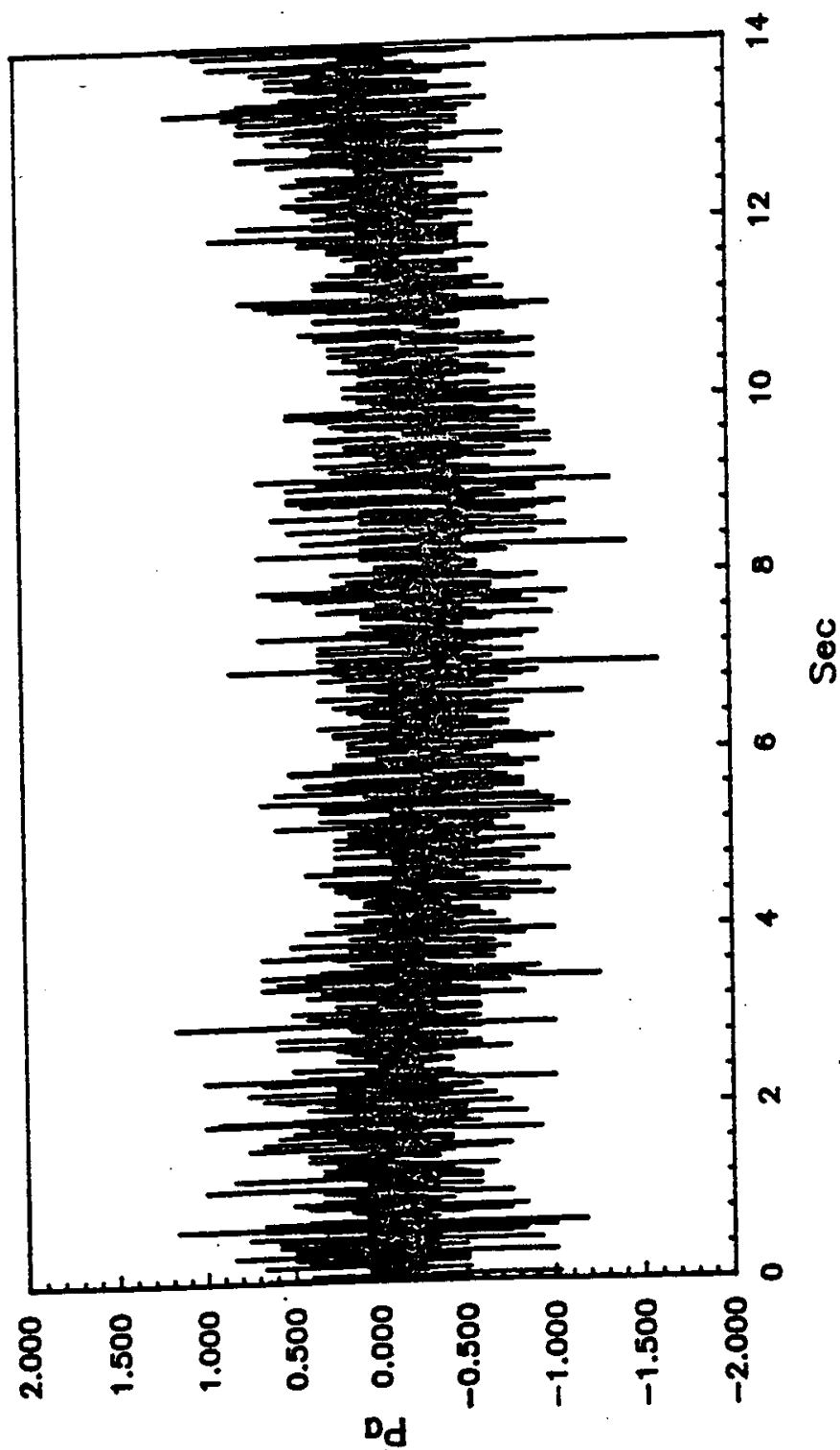


Figure 24. Measured overpressure at Miller's backyard (Survey 6).

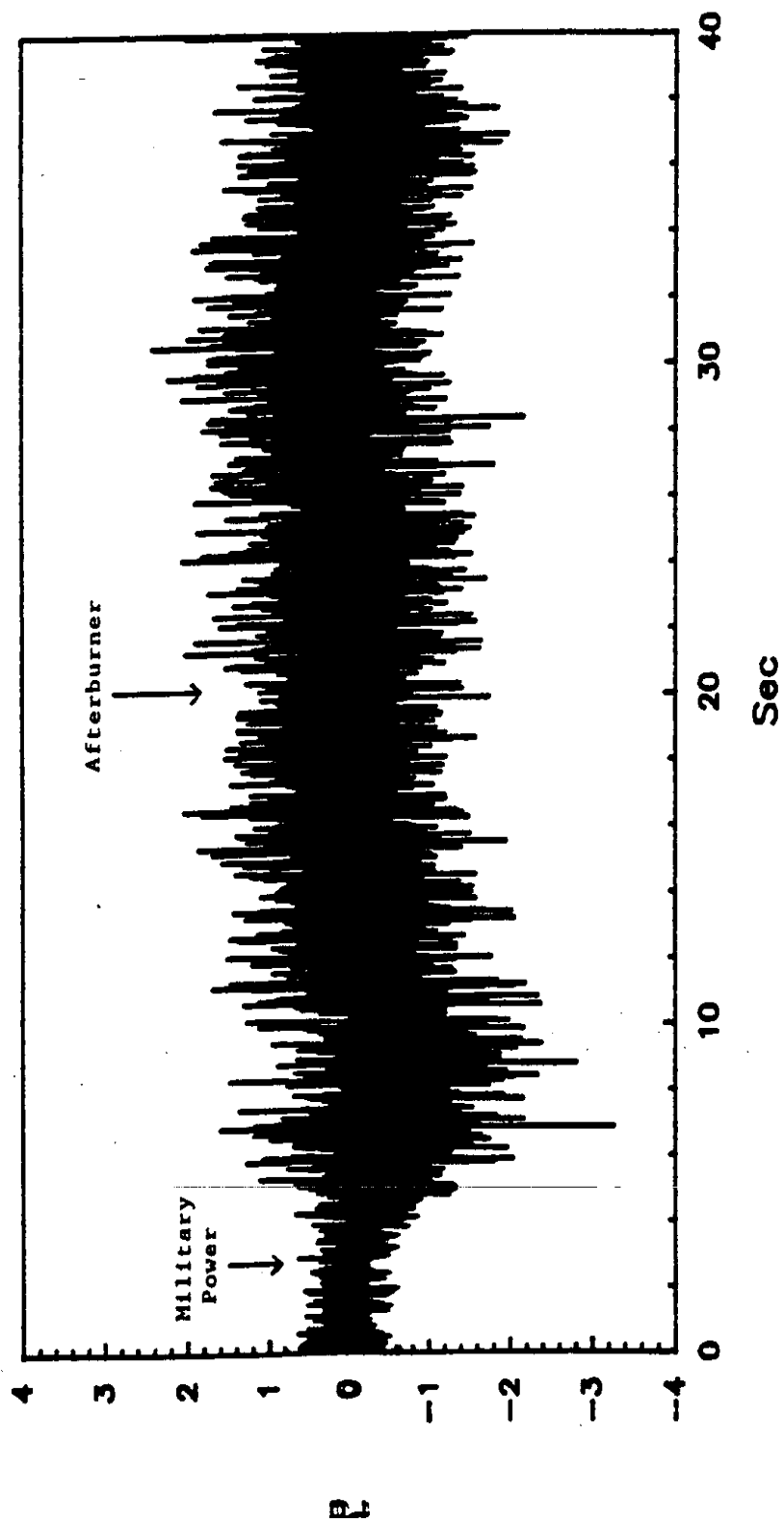


Figure 25. Measured overpressure at Miller's backyard (Survey 10).

TABLE 1. Acoustic overpressures at the Miller's residence and related atmospheric conditions.

DATE/ TIME/ SURVEY*	HGT (KFT)	TEMP (C)	WIND (AZM/KTS)	CHNAGE IN SOUND SPEED FROM SURFACE TOWARDS MILLLER'S (180) (M/S)	AVERAGE PEAK-TO PEAK ACOUSTIC OVERPRESSURE IN MILLER'S BACKYARD
1/30/90	0.0	9.0	170/02	0.0	
1800L	0.5	9.5	190/10*	-3.6	
SURVEY 7	1.0	10.0	"	-3.3	0.25
	1.5	9.0	"	-3.9	(Figure 23)
	2.0	8.0	"	-4.5	
1/30/90	0.0	6.5	295/08**	0.0	
0800L	0.5	6.1	303/15	2.2	
SURVEY 6	1.0	5.7	306/22	4.4	2.0 PA
	1.5	5.6	308/24	5.1	(Figure 24)
	2.0	5.7	310/25	6.1	
1/31/90	0.0	3.7	023/03**	0.0	
0715L	0.5	4.7	359/07	2.6	
SURVEY 10	1.0	5.7	352/07	5.2	4.0 PA
	1.5	6.3	357/11	5.6	(Figure 25)
	2.0	6.9	001/12	6.4	

* winds above surface estimated for Langley AFB using Greensboro, NC

soundings.

** winds and temperatures calculated by the USAF Environmental Technical Applications Center, Scott AFB, IL from point analyses.

on afterburner in Hush House 2. During survey 7 (30 Jan/1800L) the winds aloft were blowing with a strong southerly component. This led to minimal refractive effects toward the Miller's residence.

In the other two cases, wind speeds were increasing from the surface to 2,000 ft with a strong component toward the Miller's residence. This resulted in higher sound speeds with increasing altitude and, therefore, greater refractive effects in the Miller's direction. The strong radiation inversion on the morning of the 31st (survey 10) led to additional refractive effects and overpressure that caused the Miller's residence to vibrate noticeably, while it did not during the other surveys. Figure 26 displays peak -to-peak overpressure measured at stations 500 ft from the exhaust deflector, at Eagle Park, and at the Miller's backyard on survey 10 along with two near field measurements taken on survey 12. Although the overpressure measured in the Miller's backyard during survey 10 was relatively small (4.0 Pascals peak -to-peak), the frequency of the energy was near the natural frequency of the house (see structural analysis) and was apparently of sufficient amplitude to bring about resonance.

During both temperature inversion and surface wind duct conditions, the atmosphere can act like a lens to refract or bend acoustic energy such as the emissions from Langley AFB's hush houses. An increase in temperature and wind speed with altitude will refract acoustic energy toward the ground surface while a decrease will refract the acoustic energy (overpressure) away from the ground. Ristvet (1987) concluded for surface high explosive detonations during extreme atmospheric conditions (i.e. temperature inversions and/or wind ducts), "Overpressure at long ranges may be three to seven times the values expected in a calm homogeneous atmosphere.. Sections 4.3 and 4.4 provide a more in depth description of how inversions and surface wind ducts affect the propagation of acoustics from T-10 Hush House emissions on Langley AFB.

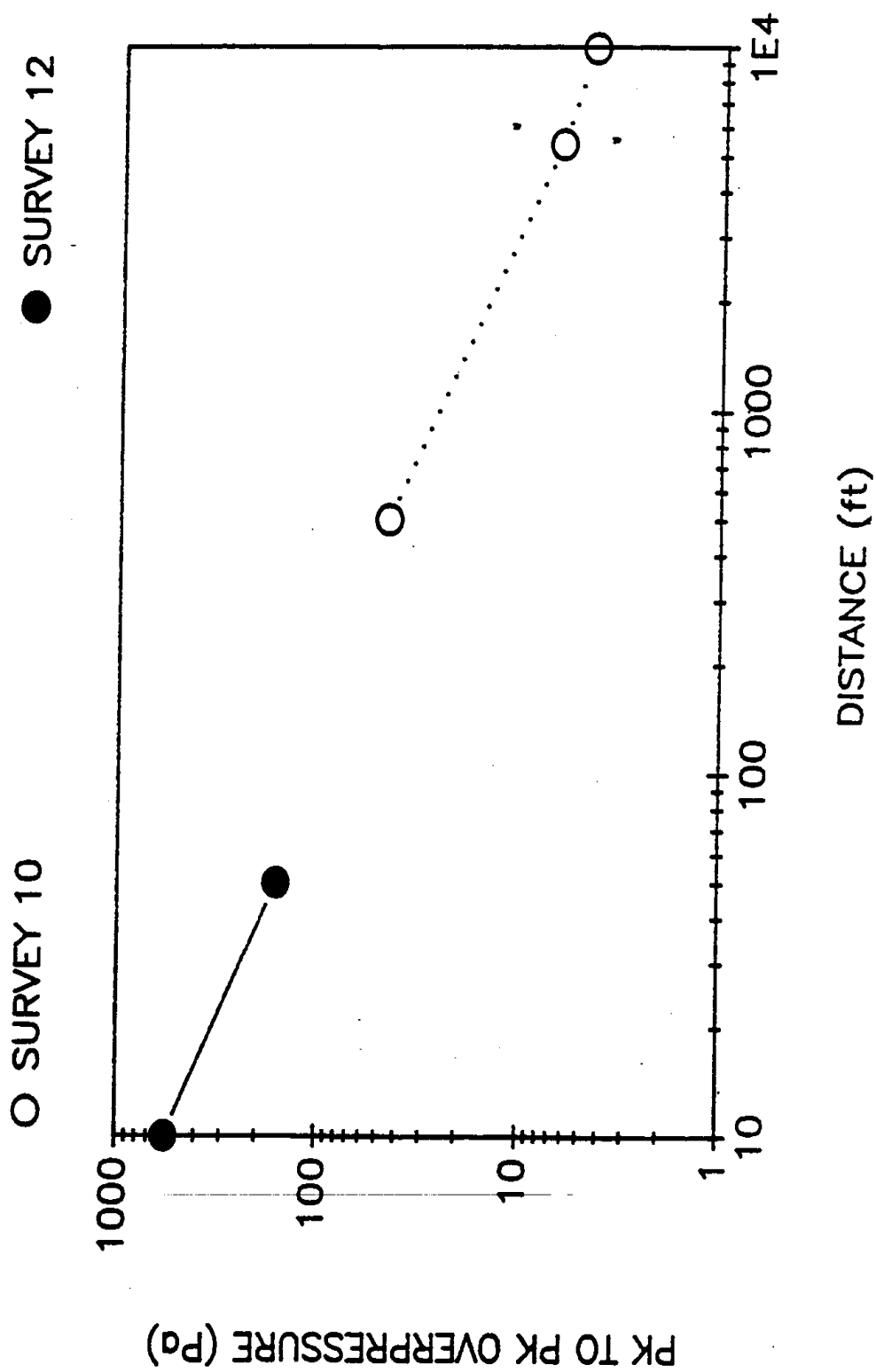


Figure 26. Measured overpressure during the F-100 engine afterburner

4.3 INVERSIONS

A temperature inversion is an atmospheric phenomenon marked by a temperature increase with altitude. With this condition, the speeds at which the individual rays from an acoustic wave will travel will increase with altitude. This is due to the fact that the speed at which an airblast wave will travel at a given level is due to the temperature at that level (as well as the wind velocity component). It is this speed increase that causes the acoustic wave to refract toward the surface and focus an inordinate amount of energy along the ground.

Since the Miller residence is 1.88 miles from the hush houses, only a low-level temperature inversion could lead to significant refraction toward the surface in such a short horizontal distance. The radiation inversion present during survey 10 (0715, 31 Jan 90) was such a low-level effect. A radiation inversion results from radiational cooling of the ground surface on calm, clear nights. The formation of a radiation inversion is hindered by cloud layers that trap heat near the surface or strong winds that mix heat within layers near the surface.

Other types of low-level inversions include those due to frontal passages or sea breezes. At the junction between a cold and warm air mass, the denser cold air will underlie the warmer air creating a temperature inversion. The inversion will be shallow right at the leading edge of the colder air. A sea breeze arises due to differential heating between a coastal land mass and the nearby sea surface. The high thermal inertia of large bodies of water causes the water to change temperature slower than the land surface. The warmer land air masses rises and is replaced by the cooler air from above the sea surface. The top of the resulting temperature inversion would usually be within several hundred meters above the surface (Perkins, 1974). Sea breezes are strongest at midafternoon when inland surface temperatures are at their maximum.

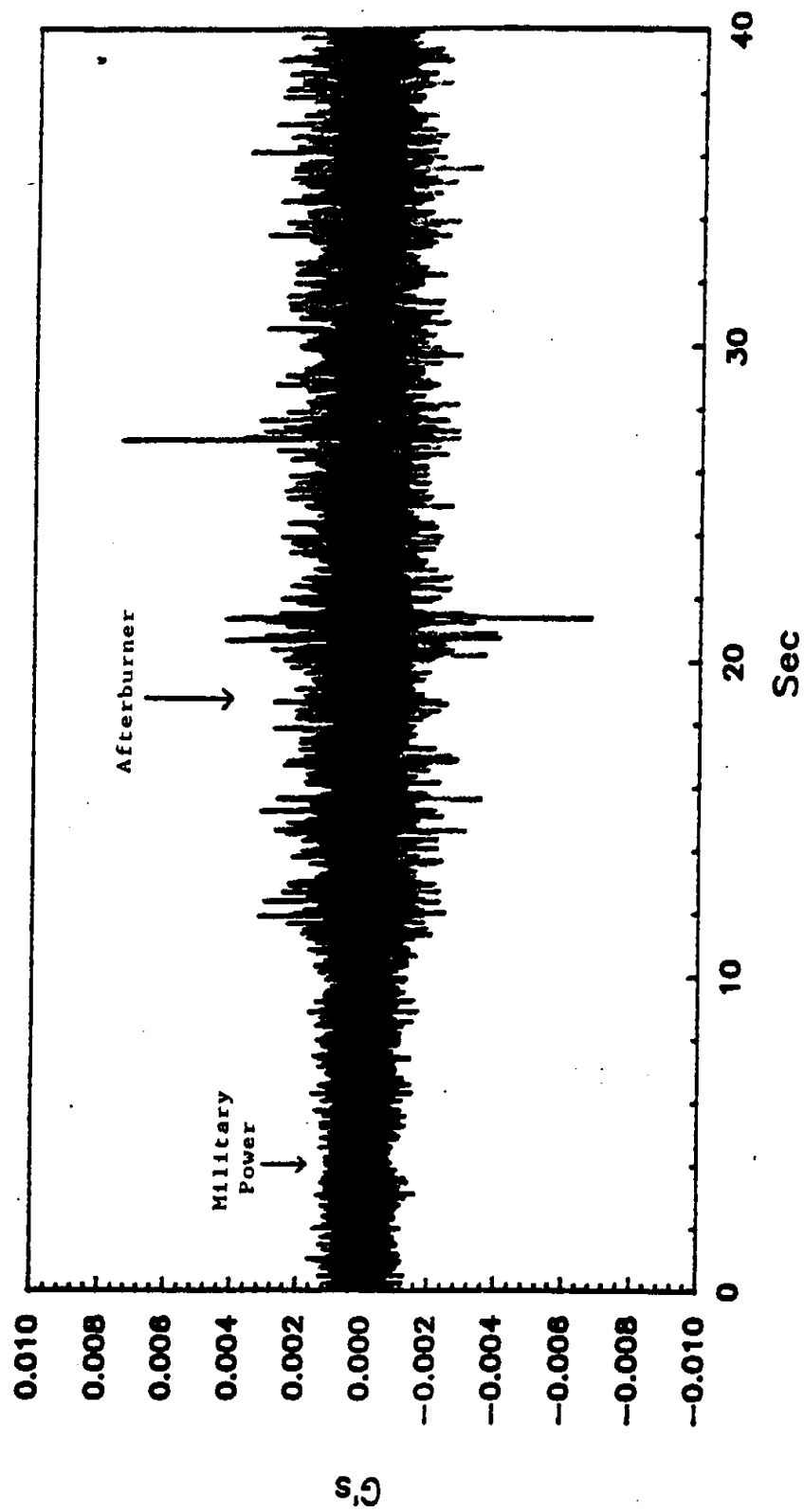


Figure 27. Measured vertical acceleration at Miller's downstairs den (Survey 10).

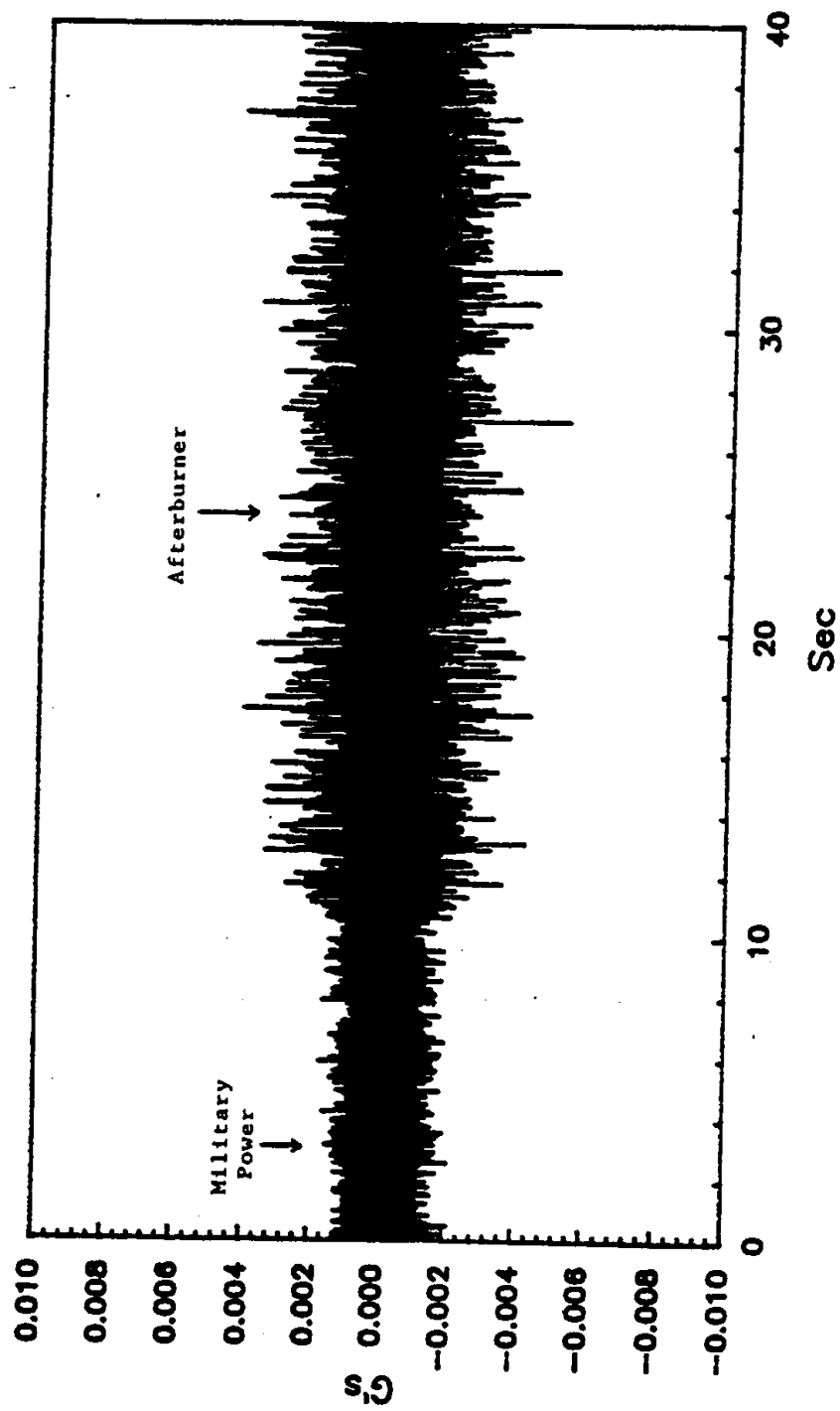


Figure 28. Measured vertical acceleration at Miller's upstairs bedroom
(Survey 10).

While inversions from radiational cooling, frontal passages and sea breezes could all refract energy from Langley AFB's hush houses, the frequency of inversion conditions at Langley AFB is relatively low as compared to inland stations. The percent of total hours of low-level inversion or isothermal conditions at Langley would be between 20% in winter and approximately 20% in summer (Hosler, 1961).

4.4 SURFACE WIND DUCTS

Surface winds blowing toward a particular target near an acoustic source can also focus acoustic energy on that target. As outlined in the ANSI standard 52.20 -1983, wind speed usually increases with height in the first few hundred feet above the surface since flow right at the surface of the ground is retarded by friction. With a 10 knot wind at 10 m above the ground, one can expect a layer up to 100 m deep, called a surface wind duct, with wind speed increasing with altitude. In the absence of opposing thermal refraction, a surface wind duct can refract acoustic energy toward the ground surface downwind from an acoustic source.

We were presented with a log listing each time the hush houses had been shut down from Feb 89 to Jan 90 due to complaints from the Millers. Correlating these shut down times with surface weather conditions recorded at the weather detachment at Langley, we found that in 21 cases, 15 were accompanied by winds with a component from the north while 6 were accompanied by calm conditions.

The Miller's residence lies on a 180 degree radial from the hush houses, and the hush house augmentor tubes point toward a 205 degree radial. Therefore, one would expect a surface wind duct toward the Miller's to set up best with surface winds blowing from the north by northwest. The log of hush house shutdowns does not indicate the severity of the vibrations that the Millers were experiencing when they called the base, so an exact conclusion as to what surface winds lead to the most serious vibration problems cannot be drawn at this time.

4.5 STRUCTURES

Structural analysis was performed to answer the following questions concerning infrasound effects on structures and attenuating the infrasound emissions from the hush houses: (1) What structural reasons cause the Miller's residence to vibrate under loading from low amplitude infrasonic acoustic waves? (2) What structural modifications to the hush houses should be accomplished to alleviate the infrasound problems experienced by the Millers?

(1) What structural reasons cause the Miller's residence to vibrate under loading from low amplitude infrasonic acoustic waves?

There are three reasons why the Hiller's wood framed, two -story structure undergoes vibrations due to the infrasound which is emitted from Langley AFB's T -10 Hush Houses:

1. The Miller's residence is of wood framed construction, therefore, it is very light and flexible and has a low stiffness value. Structures which have low stiffness values also have low natural frequencies.

2. The fact that the structure is two stories tall adds to its flexibility, further lowers its natural frequencies, and increases the area for acoustic loading. This is the primary reason why the Millers complain about the hush house emissions more than their neighbors. Their neighbors' houses are wood framed and are subjected to the unobstructed acoustic energy flow from the hush houses, but they are single -story. Also, the second story of a two story house will experience larger amplitude vibrations during acoustic loading than the first story. Floor acceleration measured on survey 10 in the first story of the Hiller's residence was lower in amplitude than acceleration measured on the second story (0.0055 g's versus 0.0075 g's, Figures 27 -28).

3. The Hiller's residence has low natural frequencies and is being loaded by acoustic energy of low frequency and long duration. These conditions establish the potential for structural vibrations to occur due to resonance.

Individually and collectively, these reasons for structural excitation warrant determining the natural frequencies of the Miller's residence. What follows is a description of that analysis and the assumptions made.

4.5.1 FREQUENCY ANALYSIS FOR THE HILLER'S RESIDENCE

The construction drawings for the structure were not available for this analysis so the configuration and location of the load bearing walls were assumed based upon observation. The dimensions and the weights the structure and its components were also assumed, again based upon observation, as well as prior knowledge of similar construction. The frequency analysis was conducted in two directions: parallel to the load and perpendicular to the load. These directions were assumed to be in line with the major axes of the structure since the structure is a long distance (1.88 mi) from the source.

The equation involved in this analysis is:

$$(K - mw^{*2})(o) = 0$$

where:

K = element stiffness (load bearing shear walls)

m = translational and rotary masses for each story (rotary mass not used here - wall configuration precludes torsion)

w = angular frequency (2 -- structure has two modes in which to respond due to its two degrees of freedom - one per story)

o = vector of modal responses (2 -- see "w")

In accordance with the equation listed, in order for the modal response vector to have non-zero value, the bracketed term must equal zero. " w^2 " is thus obtained by inserting the "K" and "m" values and solving the resulting simultaneous equations. The result is a root for each of the two response modes. The square roots of these solutions represents the angular frequencies of the modes. Dividing by the number of radians in a circle yields the natural frequency for each mode.

The translational "m" values are the same for each direction of loading. The weights of the first and second stories are calculated by adding together the weight per square foot of the components comprising the respective story, and then multiplying by the plan area of the structures. The masses are then calculated by dividing by gravity.

The "K" values differ for each direction of loading because the different elements (walls) have different roles in distributing the load in each

4.5.2 STRUCTURE STIFFNESS IN THE DIRECTION OF THE LOAD

The walls of the structure determine its stiffness and their respective involvement for this case as follows: the two exterior walls parallel to the load (sides of the house), the wall in the middle of the structure (walls which bound stairway were assumed to act as one wall running the length of the structure) carry both bending and shear, and the two exterior walls perpendicular to the load (front and back of the house) carry only bending. The exterior walls have brick veneer on them which was included in calculating story mass but neglected in calculating stiffness because the veneer is not structurally attached to the foundation (veneer serves as an architectural finish, not a structural element). All walls, therefore, were assumed to be of the same composition, and geometrical and material properties. This allows for a 2x2 stiffness matrix; four values (one value for each of the four degrees of freedom which arise from the two response modes). This 2x2 matrix is obtained by inverting the 2x2 deformation matrix. Each degree of freedom in the deformation matrix has a shear

deformation component and a bending deformation component. These components are summed for each degree of freedom and placed in their respective place in the matrix. The two walls of the structure which carry only bending deformation have their contributions 'smeared' in with the walls parallel to the load direction.

The natural frequencies (f) for this case are:

f (first mode) - 7.4 Hz
f (second mode) - 18.33 Hz

Structure "K" In The Direction Perpendicular To The Load

The involvement of the walls for this case is: the front and back walls which are perpendicular to the load, now carry both bending and shear; and the side walls of the house, as well as the wall parallel to the side walls in the middle of the house, will carry only bending.

The "f" values for this case are:

f (first mode) - 8.6 Hz
f (second mode) - 21.3 Hz

The "f" values for each case are in line with what is typically seen for residential structures. The larger moment of inertia and cross-sectional shear area reduced the bending and shear deformation values, respectively, in the second case. This yielded higher stiffness values, therefore, higher natural frequencies.

Spectra analysis of floor vertical acceleration data obtained from Miller's upstairs on survey 10 (Figure 29) shows a first mode at approximately 18 Hz and a secondary mode at 34 Hz. The first modal frequency for the floor acceleration shows good correlation (18 Hz) with the second modal frequency (20 Hz) that was calculated for wall acceleration. Although, we are unsure

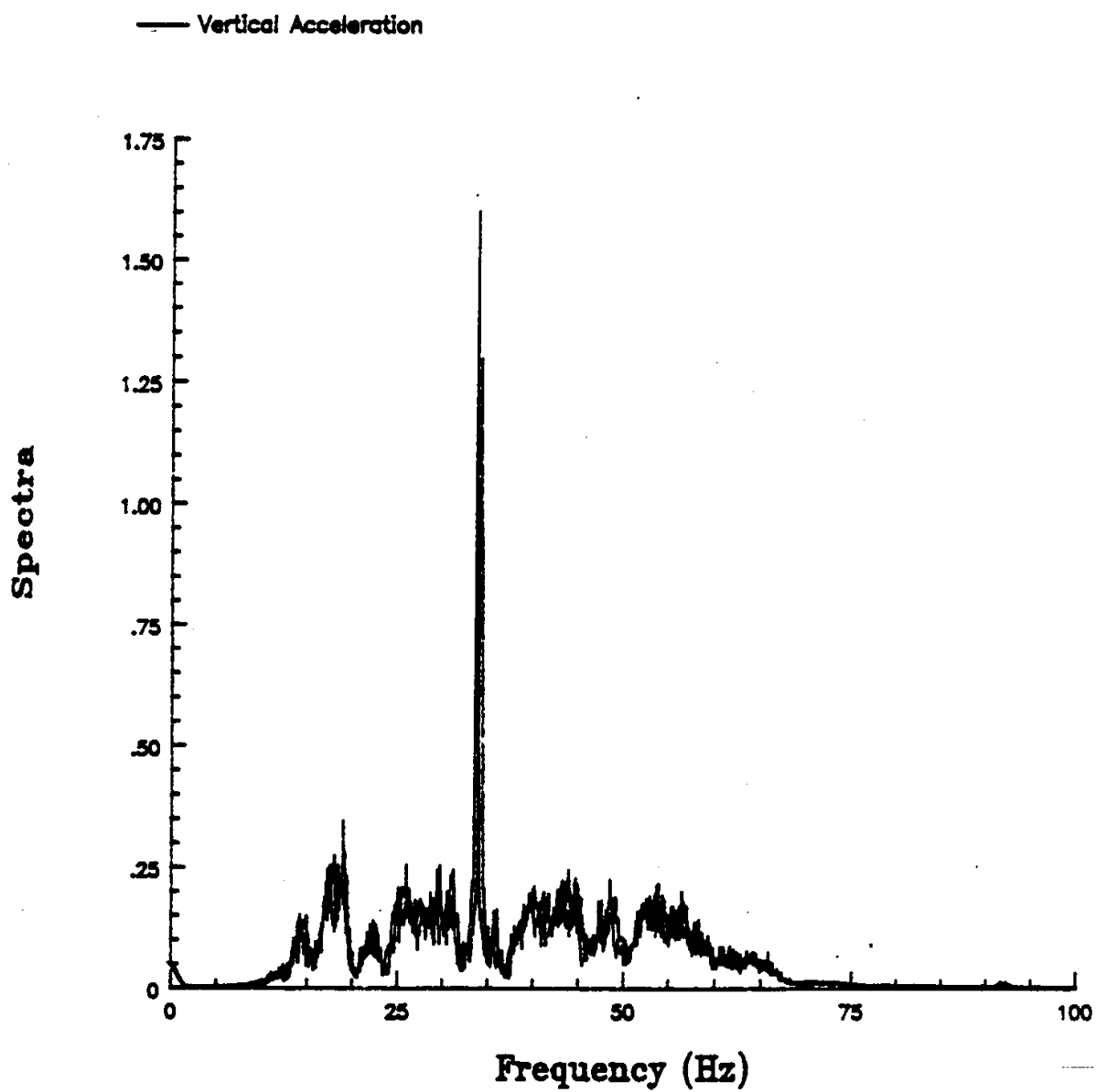


Figure 29. Frequency spectra on measured vertical acceleration at Miller's house, upstairs (Survey 10).

of the relationship between the floor and wall fundamental modal frequencies, the floor acceleration may be due to coupling with the wall vibrations with a predominant frequency near 20 Hz.

The spectra analysis data and the natural frequency calculation for the residential structure shows that there may be a resonant condition with the source loading. The second nodal wall frequency and first modal floor frequency for the structure are near 20 Hz, and the predominate frequency of the acoustic load is 15 to 25 Hz.

Witten (1987) stated that long -term structural damage may occur for wall accelerations greater than 0.01 g's. The largest ground (floor) acceleration measured in this study was 0.0075 g's (Figures 13 - 28). Although , wall acceleration was not measured in this study, we believe that neither the intensity of the vibrations nor the acoustic loading appear to be detrimental to the structure in the near term. However, if this structure is subjected to continued acoustic loading in the long term (10-15 years), there is a strong likelihood that it will become structurally and most certainly, architecturally damaged. As a minimum, it can be expected that the nails which connect structural elements will become loose. Thus, the house will become noisy when it is subjected to light winds, foot traffic and other minor forms of loading under which a structurally sound house would not be expected to make noise.

Architecturally, brick veneer Joints will open up and require re -mortaring to prevent the bricks from coming loose, window and door seals will lose their air -tightness and insulating capabilities, and the sheetrock Joints will crack and require re-taping and plastering.

To directly measure wall accelerations at the Miller's residence, we would have to directly connect an accelerometer to the wall. This direct connection would require bolting or some other method that would damage the wall. However, given additional funding, we could determine the wall acceleration with data collected in this study and with calculation methodologies available in the literature. Work has been completed

concerning the determination of wall accelerations for various types of wall construction exposed to aircraft infrasound. Having completed this additional study, we would be able to better determine the long term effects of the structural vibrations on this house.

(2) What structural modifications to the hush houses should be accomplished to alleviate the infrasound problems experienced by the Miller's?

According] to Witten (1987), "Mitigation of infrasound problems can be accomplished by means of hush house design, siting criteria, nearby land-use constraints, or modified construction practices for buildings to be located near a hush house. (Witten, 1987). Since the Millers are already experiencing vibration problems due to hush house emissions, a redesign of the hush house is the only viable alternative to alleviate the problem. However, Witten further states that a "modification to the hush house design to alleviate vibration problems requires an understanding of the mechanism(s) which are responsible for the infrasonic emissions, a quantification of the source characteristics, and a description of the resulting far -field pressure levels." Therefore, any modification to the hush house structure should be researched intensively both before and after implementation in order to understand how it effects the phenomena mentioned by Witten.

At the 1 Feb 90 briefing at Langley AF8, TAC/DEE decided that a modification to Langley AFB's T -10 Hush Houses to disrupt the infrasonic flow would be accomplished to alleviate the problem TAC/DEE's chosen method, which was proposed by AFLC/SA -ALC, was the placement of turning vanes at the end of the augmentor tube. The vanes, which are curved steel plates, are supported by steel bars and are oriented so to introduce turbulence and a vertical component to the exhaust flow that exits the augmentor tube. The current exhaust deflector is displayed on Figure 30 and the proposed turning vanes are displayed on Figure 31. The cost estimate given for this alternative was \$200k per hush house. Since this system has been successfully implemented at two other AF bases it should alleviate Langley AFB's

infrasound problems. However, a possible problem with this modification is that it may introduce some back pressure into the augmentor tube during engine testing.

During the briefing a few other modifications to the hush house were discussed. A modification that was proposed by Dr. Alan Witten of Oak Ridge National Laboratory calls for placing steel plates, in a venetian blinds type arrangement, in the last outside air inlets located on both sides of the hush house structure. The plates on one side would be angled up and on the other side down, thereby creating a turbulent environment as the outside air is drawn into the augmentor tube. Some of the infrasound is destroyed in this manner. This proposal has not been cost estimated but is believed to be fairly expensive. Also, this modification has not been tested yet.

A modification that was proposed by Weapons Laboratory calls for placing a berm composed of select fill directly behind the exhaust deflector. This modification would attenuate the infrasound that permeates through the panel but would not affect the majority of the acoustic energy that is deflected over the panel. The 'acoustic overpressure' section of this report contains more detail concerning this proposed. As summarized before, this modification would be inexpensive to implement and could be used along with the primary solution (turning vanes, etc.) to provide even greater attenuation of the infrasound.

Another modification that may solve this problem is one that we will investigate if given additional funding. This modification includes welding a steel plate to the top of the exhaust deflector. This plate would be a vertical extension of the exhaust deflector and would be continuous over the width of the panel. The plate would force the acoustic energy, which now has a directional component, to behave as a vertical flow. Perhaps some curvature of the plate toward the hush house source would be required to completely delete the directional component. If the curvature required is extreme, a pipe could be cut in half (lengthwise) and installed as the plate. The thickness of the plate required would be determined from the

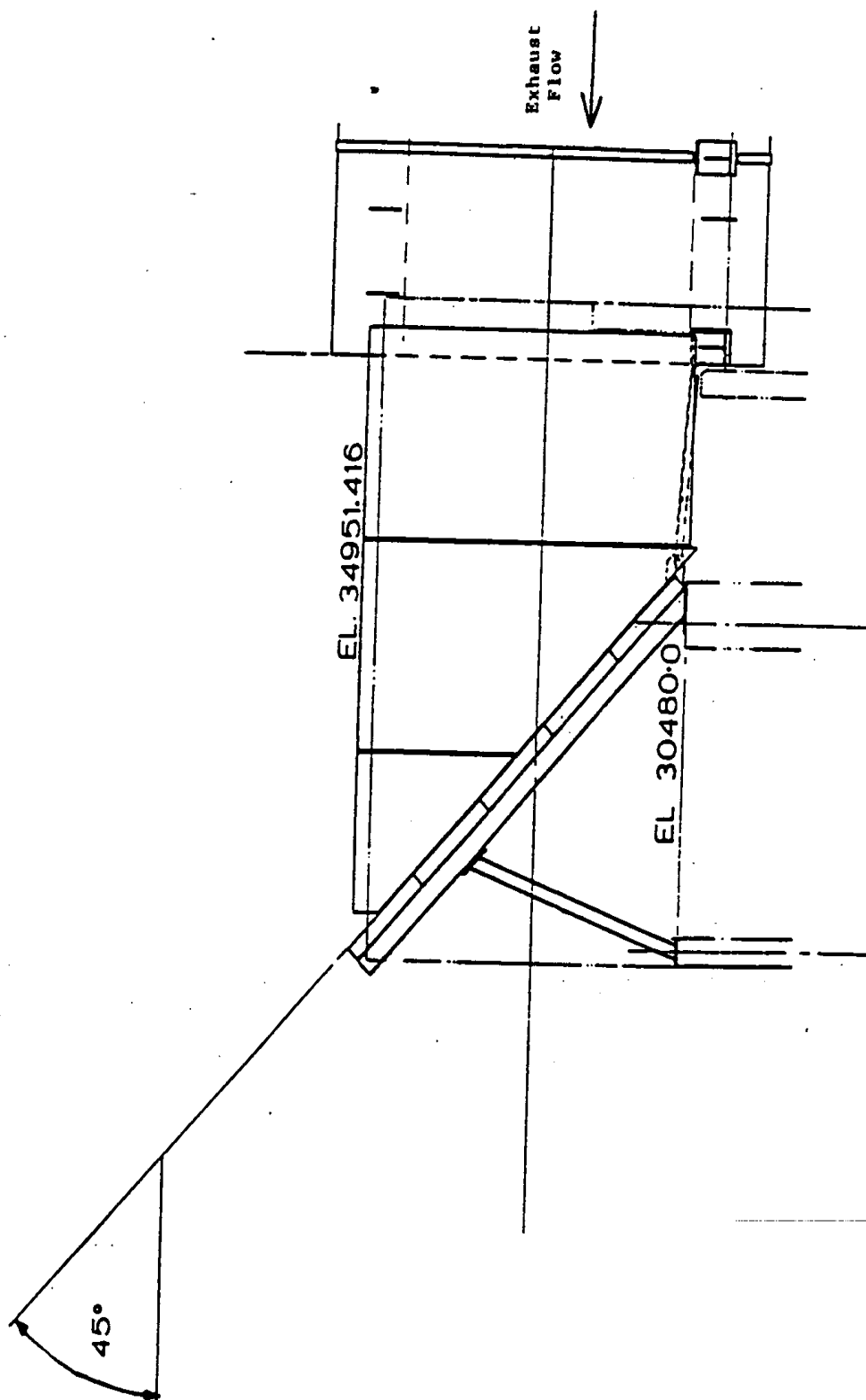


Figure 30. Current exhaust deflector.

force acting upon it, which is caused by the mass and acceleration of the acoustic energy impinging upon it (the acceleration comes from the change in velocity as the acoustic waves change direction upon striking the exhaust deflector). To provide support for the welded connection, steel beams could be introduced in the same manner as what is now used to support the exhaust deflector. If this alternative proves to be viable, its implementation would not introduce any back pressures into the augmentor tube and it would be relatively inexpensive as compared to the cost of the turning vanes.

5.0 CONCLUSIONS

Infrasonic emissions from Langley AFB's two T-10 Hush Houses are the cause of the vibrations occurring at the Miller's residence which is located 1.88 mi (9,925 ft) due south of the hush houses. The infrasonic emissions are transmitted as low frequency acoustic energy (acoustic overpressure) along an unobstructed path towards the Miller's residence. The low frequency, long duration, acoustic energy vibrates the Miller's residence when it is of sufficient amplitude. The structure did not vibrate noticeably when the measured peak-to-peak acoustic overpressure was 2.0 Pa, but it did when the peak-to-peak acoustic overpressure was 4.0 Pa. Ground motion was not found to be a significant contributor to the vibrations at the Miller's residence.

The variance in acoustic overpressure measured at the Miller's residence (0.25 to 4.0 Pa) during F-100 engine afterburner testing in Hush House 2, was due to the effects of the atmosphere on the acoustic energy propagation. Surface wind ducting (with northerly winds) and temperature inversions are two atmospheric conditions that increase the overpressure in the Miller's direction. Surface wind ducting is probably the key atmospheric contributor since the frequency of northerly winds is much higher than that for inversion conditions. This is especially true from October through March when the average surface wind at Langley is from the north.

Listed below are several aspects concerning the hush house as an infrasonic source that have a significant affect on the acoustic energy propagation towards the Miller's residence:

- (1) Infrasonic emissions behave as a near monopole source located at the rear of the hush house (Witten, 1988).
- (2) infrasonic emissions increase in magnitude substantially at higher engine power levels such as from military power to afterburner (Witten, 1988).

- (3) An uninstalled F -100 engine produces larger amplitude acoustic overpressures at medium to long ranges than an installed F -100 engine (F -15 aircraft) while running on afterburner in the hush houses.
- (4) Hush house infrasonic emissions have an intrinsic directional component in the radial direction of the exhaust flow through the augmentor tube. At Langley AFB this directional component is toward the south (Miller's residence) to southwest.
- (5) The acoustic energy that permeates through the hush house's exhaust deflector has a lower predominant frequency than the acoustic energy that gets deflected over exhaust deflector.

There are three structural reasons why the Miller's residence vibrates under loading from low amplitude infrasonic acoustic energy:

- (1) The Miller's residence has a low stiffness value due to its light weight wood framed construction.
- (2) The house is two stories tall which not only increases the area for acoustic loading but adds to the structure's flexibility.
- (3) The house has a low natural frequency (second nodal wall frequency is approx. 20 Hz) that is near the predominant frequency (15 to 25 Hz) of the acoustic energy. Thus, the low frequency acoustic energy load may be resonating the Miller's residence.

Witten (1987) stated that long -term structural damage may occur for wall accelerations greater than 0.01 g's. The largest vertical floor acceleration measured at the Miller's residence in this study was 0.0075 g's. While the vibrations measured at the Miller's residence are relatively mild and pose no short -term structural damage threat, the possibility for structural damage over the long -term is highly probable.

6.0 RECOMMENDATIONS

1. According to Blevins and Witten (1987), "the USAF presumes that vibrations from hush house infrasonic emissions may be detectable up to 5000 ft with special equipment, a potential concern for sensitive land use functions at 3000 ft, and a possible problem within 1000 ft.. Since the Miller's residence is experiencing vibration problems at a distance of 9,925 ft away from the hush houses, the Hush House Site Planning Bulletin siting distances should be increased to satisfy the findings in this study
2. In order to stop the vibrations at the Killer's residence, Langley AFB's hush houses should be modified to attenuate infrasonic emissions as soon as possible. Since the implementation of turning vanes at the end of the augmentor tube is the only proven method for alleviating the infrasound problems, these vanes should be installed. However, very little is known concerning the effects this modification will have on the infrasonic acoustic energy in and around the hush house. For instance, this modification may introduce some back pressure into the augmentor tube during engine testing. Therefore, a far -field and especially a near -field (around the exhaust deflector and the augmentor tube) vibroacoustic study should be completed both before and after implementation of this modification in order to better understand the effects the vanes have on the hush house emissions.
3. Until a solution can be implemented (i.e. turning vanes, etc.) to sufficiently attenuate Langley AFB's hush house infrasonic emissions, the operation of the hush houses should be restricted. Engine testing in the hush houses should not be done during periods of moderate to strong northerly winds (> 5 knots) and/or during temperature inversion conditions. If complaints persist under these restrictions, the wind restriction should be increased to include periods with any north wind component.
4. Witten (1987) stated that a modification to the hush house design to alleviate vibration problems requires an understanding of the mechanism(s) which are responsible for the infrasonic emissions, a quantification of the

source characteristics, and a description of the resulting, far -field pressure levels." We believe that research should be done to understand these mechanism(s). After achieving this understanding, the research should then focus on finding a modification to the hush house that would attenuate the infrasonic emissions without affecting the engine testing or increasing the audible emissions that the hush house was primarily designed to attenuate. This modification should then be implemented into the design for all T-10 Hush Houses. The research should also address each of the modifications that were addressed in this survey (1) Turning vanes at the end of the augmentor tube, (2) Steel plates in a Venetian blinds type arrangement in the last air inlets in the hush house, (3) Placing a select fill berm directly behind the exhaust deflector, and (4) Placing a vertical steel plate on the top of the exhaust deflector.

5. We believe that the infrasound caused vibrations in the Miller's residence will damage the structure in the long term (10 - 15 years). More research should be completed to determine with more certainty the extent of the damage and when it could be expected to occur. The UL has the data and the structural engineering expertise to confirm this research.

6. Battis (1987) provided a near -field model for acoustic emissions from T10 Hush Houses. We propose that Battis's model should be expanded to include far -field atmospheric effects on these acoustic emissions. Since the hush houses emit low overpressure, low frequency acoustic energy, atmospheric conditions greatly affect its propagation in the far -field. In order to numerically quantify these atmospheric effects, hydrocode modeling should be accomplished followed by test validation of the proposed model. The WL has the expertise in hydrocode modeling and acoustic field testing to provide such a model.

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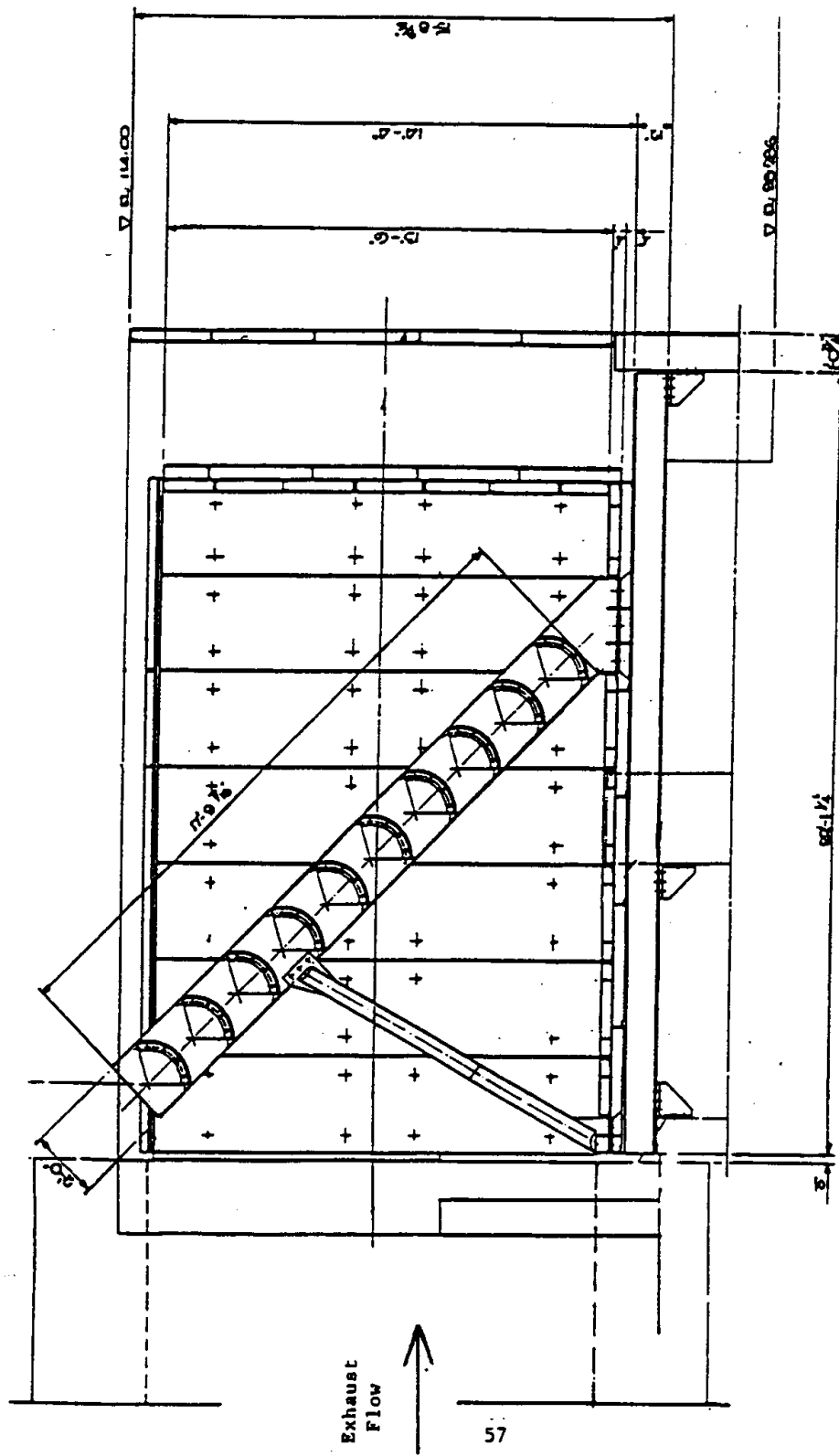


Figure 31. Proposed turning vanes.

Hush House Induced Vibrations at the Arkansas Air National Guard Facility, Fort Smith, Arkansas

JAMES C. BATTIS



13 November 1987



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Mr. Roger Blevins
HQ AFLC/DEPC
Wright-Patterson AFB, OH 45433-5000



EARTH SCIENCES DIVISION

PROJECT 7600

AIR FORCE GEOPHYSICS LABORATORY

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<p>The T-10 jet engine ground run-up noise suppressor, or Hush House, was designed to reduce the audible effects of jet engine testing on the surrounding community. At least in part, the noise suppression characteristics of the Hush House are achieved by the transfer of energy from the audible (20 Hz) to the infrasonic range (< 20 Hz). At some sites these lower frequency emissions have had deleterious effects on the vibro-acoustic environment of nearby buildings. This report describes a case study on this problem and demonstrates that existing siting criteria for the Hush House are inadequate; in one case being too stringent and in another case too lax. An acoustic emissions model for the Hush House is proposed based on multiple jet type sources.</p>			
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22a. NAME OF RESPONSIBLE INDIVIDUAL James C. Battis		22b. TELEPHONE (Include Area Code) (617)377-3222	22c. OFFICE SYMBOL AFGL/LWH

Hush House Induced Vibrations at the Arkansas Air National Guard Facility, Fort Smith, Arkansas

1. INTRODUCTION

1.1 Background

The T-10 jet engine ground run-up noise suppressor, or Hush House, (Figure 1), was designed to reduce the audible impact of necessary jet engine testing on the surrounding community and to allow siting of the test function closer to the maintenance operations that it supports. At least in part, the noise suppression characteristic of the Hush House is achieved by the transfer of energy from the audible (> 20 Hz) to the infrasonic (< 20 Hz) range. At some sites these lower frequency emissions have had deleterious effects on the vibro-acoustic environments in nearby buildings. In one instance, sufficiently intense disturbances were reported to raise questions concerning both the structural safety and health of the occupants. In May 1984, the Air Force Geophysics Laboratory (AFGL) was requested by Air Force Logistics Command (AFLC) to assist in the development of siting criteria to mitigate these problems for the T-10 Hush House. At that time AFGL/LWH recommended that AFLC consider the development and application of a sitespecific vibro-acoustic forecast method based on techniques previously developed by AFGL

(Received for publication 29 October 1987)

1. Personal Communications, Maj. William Ponder, USAFR, October 1984.

to support Space Shuttle operations at Vandenberg AFB, California. 2.3 It was felt that this technique could be modified for use in Hush House site selection and to minimize post-construction disturbances on operations in nearby structures.

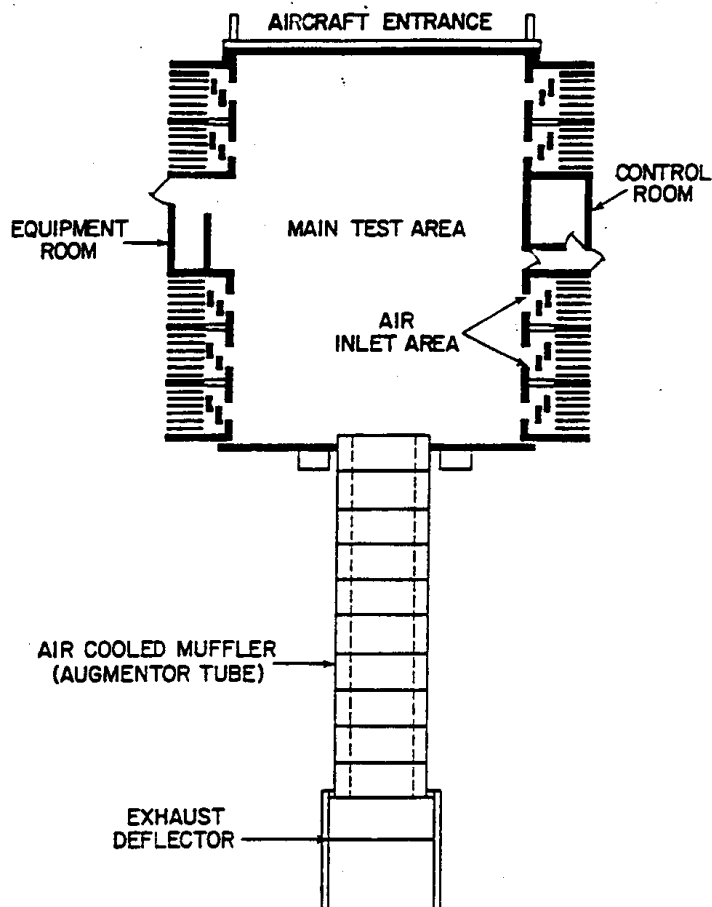


Figure 1. Plan View of the T-10 Hush House

2. Crowley, F.A., and Hartnett, E.B. (1984) Vibro-Acoustic Forecast for Space Shuttle Launches at VAFB, The Payload Changeout Room and the Administration Building AFGL-TR-84-0322, ADA 156944, Hanscom AFB, MA.
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The effort to refine this methodology for application to the Hush House problem started with a preliminary field study conducted at Luke AFB, Arizona in September 1984. This study demonstrated several facts relevant to the Hush House siting problem. First, the dominant cause of induced vibro-acoustics in structures near the Hush House is airborne infrasonics. Second, the propagation characteristics of the Hush House infrasonic emissions can largely be explained as spherical propagation from an azimuthally dependent source located 10 m above the exhaust deflector at the end of the augmentor tube (Figure 1). Finally, and as was expected, the response of the impacted structures depends not only on range from the Hush House, but also on the relative orientations of the infrasonic noise source, that is, the Hush House, and the impacted structure. Using methods developed by AFGL, it was shown that well over 90 percent of the observed energy in the Hush House induced vibrations can be forecast given adequate knowledge of the source. Taken together with other findings from this work, the Luke study supported the feasibility of forecasting, prior to construction, the environment in neighboring structures that would be impacted by Hush House operations.

Analysis of data taken at Luke AFB also motivated the development of a hypothetical source model for Hush House acoustics. This working hypothesis is discussed in Appendix A. Basically, the model assumes that the acoustic emissions are generated by turbulence associated with the air intakes and exhaust of the Hush House. The characteristic spectral form for the emissions is a bell shaped curve, peaking near 15 Hz, due to the exhaust jet, with a weaker secondary lobe at about 5 Hz believed to be due to the intake jets. For a given Hush House design, the locations of these peaks and the spectral levels will vary with the velocity of the exhaust and intake air. These, in turn, are functions of the size and power level of the engine being operated in the Hush House.

1.2 Hush House Siting Criteria

At-present, siting guidelines for the T-10 are based on zones of exclusion around the Hush House within which the siting of specified structures or activities are restricted. One example of this type of criterion is given in Table 1.

4. Battis, J.C., and Crowley, F.A. (1986) Forecasting Hush House Induced Vibro-Acoustics, Proceedings of NATO-CCMS, Conference on Aircraft Noise in a Modern Society, NATO No. 161, Mittenwald, Germany.
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These criteria, being generalized for wide application, must balance two conflicting issues, maximizing land use at all sites and minimizing the incidence of significant adverse impact. On one hand, to insure adequacy in a worst case scenario, the zones of exclusion can be made extremely large, resulting in poor land use in most applications. Alternatively, the zones can be reduced in size to represent more "typical" conditions with the acceptance of a higher likelihood of adverse impacts requiring post-construction corrective action and resulting increase in cost. On the positive side, this type of criteria can be made easily understandable by the end user and is simple to apply.

Table 1. Zone of Exclusion Type Siting Guidelines for F10 Hush House^o

Facility /Activity	Distance (m/ft)=	Criteria Basis
Unoccupied Facilities	5/ 16, as measured from any exterior point on Hush House 3 3/ 100. as measured from exhaust tube entrance.	No risk Of architectural damage from vibration.
Workshop (fulltime occupancy)	49/150	Noise and vibration.
Pre -engineered Buildings	115/350	Exterior panels exhibit considerable vibration.
Office	164/500	Noise
Vibration Sensitive Equipment (for example, optical microscopes, photo interpretation light tables).	328/1000	Vibration
Housing (less than four stories)	328/1000	Noise
Housing (more than three stories)	492/1500	Noise

NOTE: Distances are for minimum personal complaints.

* Radial distance as measured from both ends of the exhaust tube. The two semicircles described by the arcs, connected by straight lines at circumferences, form distance envelope.

NOTE: Above criteria developed f-o n noise and vibration surveys conducted at 149th ANG, SAALC.

- The intrinsic balance discussed above must result from the fact that a zone of exclusion type criterion is unable to account for any of the site-specific elements of the problem, primarily the site dependent effects on acoustic propagation and the unique response characteristics of potentially impacted structures. The last of these complications should be obvious to anyone familiar with structural dynamics. A useful example of the former problem has been documented at the Shuttle launch complex at Vandenberg Air Force Base (SLC-6).² Due to multipathing (echoes) of the acoustic signal at the Vandenberg complex, frequency dependent loads on structures are as much as 14 dB or five times greater than would be anticipated at the same distance from a source in an open setting, the conditions found at the Shuttle facility at Kennedy Space Center (KSC). In other words, zones of exclusion based on data from KSC would greatly underestimate the vibro-acoustic effects anticipated at the Vandenberg launch complex.

1.3 Fort Smith, Arkansas Field Study

The Arkansas Air National Guard (ANG) facility at Fort Smith provided a case with which to measure the value of existing Hush House siting criteria. At present, the ANG maintains a T-10 Hush House for testing of F-4 Phantoms. It is intended that this ANG unit will upgrade to F-16 aircraft in the near future.⁷ An existing building, the Avionics Building, could be modified to accommodate the F-16 avionics test equipment. However, based on existing Hush House siting criteria, a new facility for this equipment should be constructed at a distance of over 328 meters from the Hush House as the test equipment is considered motion sensitive. The cost of this new construction would exceed the cost of modifying the existing facility.

At the request of ANG, AFGL conducted a vibroacoustic survey at the Fort Smith facility to measure vibration levels in existing structures due to Hush House operations. This report provides the results of that survey and the implications of this effort towards the development of more efficient criteria for siting infrasonic noise sources such as the Hush House.

7. Personal Communications, Lt. Col. Steve Core, Arkansas ANG, October 1986.

6. SUMMARY AND CONCLUSIONS

6.1 Fort Smith Specific Results

In terms of the questions raised by the ANG concerning Hush House operations at the Fort Smith facility, there are three results:

- (1) The motion environment in the existing Avionics Building at Fort Smith will be degraded by Hush House operations with the F-16, but only for operations in afterburner. Present Hush House operations, with the F-4 in afterburner, generate higher motion levels than will the F-16 in military power. While the environment will be adversely impacted during F-16 afterburner runs, it will be significantly below existing EPA criteria for motion sensitive work areas. Further the levels observed at this site are several orders of magnitude below those capable of damaging the F-16 avionics test benches based on the manufacturer's specifications.
- (2) Building 221 experiences severe motions during all Hush House operations and, in particular, during afterburner runs. The motions in this building are sufficient to warrant concern for the long term safety of the structure. It is highly recommended that some form of periodic inspections be instituted to check the structural elements of Building 221 for fatigue type failure or, alternatively, that the structure be re-sited.
- (3) Finally, the motion environment at the proposed building site, approximated by the location of site 7, is not significantly higher than levels observed at other sites at the ANG facility. As Hush House infrasonics attenuate as $1/R$, the pressure loads at this site are about one-half those at the present avionics structure. A similar building, at this location and with similar orientation relative to the Hush House, should experience induced vibrations proportional to the pressure loads.

6.2 Implications for Hush House Siting

Several implications exist in the results of this study relative to the siting criteria for Hush Houses. First, that the existing 330 meter exclusion zone for motion sensitive facilities is likely to be found to be overly stringent. The present case study provides one example of a structure, essentially picked at random, in which the criterion is too stringent. In fact, using the standard R_0/R scaling law for acoustic farfield pressures, where R_0 is a reference distance and R is the

source radius to the point of interest, and assuming a radially symmetric Source, the EPA criterion for a critical work area would not be exceeded unless the Avionics Building was within 25 meters of the Hush House exhaust deflector. This assumes a standard pressure spectrum and a linear relationship between vibrations in the structure and loads. While the calculation cannot, due to the assumptions, be used as a basis for any rational criterion for Hush House siting, it does suggest the lack of a strong scientific basis for the existing criteria.

Alternatively one can look at Building 221. This structure is 80 meters from the exhaust deflector of the Hush House. To reduce the motion levels at site 4 in this structure to levels considered very unlikely to produce structural damages, 0.006 m/sec, would require moving the building out to 145 meters, beyond the 115 meters specified in Table 1. As mentioned earlier, motion levels higher up on the structure are anticipated to be even greater and would require moving the structure further out, well beyond the cited criterion for ~~one~~ engineered structures.

In terms of future scientific study on the Hush House problem, three major points should be made:

- (1) The primary fundamental modes of most substantial structures lie below 10 Hz and the motion environment in these structures will be inordinately driven by the secondary lobe of the Hush House infrasonic source.
- (2) A working hypothesis for the structure of the Hush House infrasonic source has been presented. While the hypothesis cannot be ruled out by existing data, much work remains before the hypothesis can be accepted outright. In light of the fact that proposals have been presented to alleviate the infrasonic problems with the Hush House by altering the source, it would seem desirable that one should have a well established understanding of the existing source.
- (3) If the working hypothesis is correct, then the secondary lobe of the Hush House source is the result of a "negative" jet associated with the air intakes of the Hush House. To a large degree it is this jet that will control the motion environment in nearby structures. In turn, this jet is controlled by the velocity of air entering the Hush House through the inlet ducts. As the area of the inlet ducts remains constant at least in present designs, then the velocity of the air is controlled by the volume of air entering per unit time. The volume of air entering the Hush House is related to two parameters of the engine, its size and power setting. The implication is that as one builds Hush Houses for larger engines, with or without afterburners, the volume of air entering the Hush House

will necessarily increase and the secondary lobe of the source will become increasingly powerful,

The problem of Hush House infrasonics and their effects on the surrounding Community is far from resolved. Significant areas of research remain to be done. It is hoped that this report provides some degree of insight into the problems that require further study.

OAK RIDGE NATIONAL LABORATORY

OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37831

December 2, 1986

Mr. Roger Blevins
HQ AFLC/DEPR
Wright-Patterson AFB, Ohio 45433-5001

Dear Roger:

As per the November 18 request, enclosed is a one page action plan for the Hush House study.

Sincerely,

Alan Witten

AJW:db

Enclosure

HUGH HOUSE ENVIRONMENTAL STUDY ACTION PLAN

A generic environmental study of hush house operations is being prepared in order to identify and investigate issues which could lead to siting constraints for either hush houses or facilities which could be located within an impacted region surrounding a hush house. Following a review of available literature and a comprehensive scoping effort, the identified issues to be addressed are:

- (1) Noise - while all operational T10 hush houses have satisfied the noise level acceptance criterion, this criterion is based upon spectral weighting which essentially neglects the low frequencies. These low frequencies comprise the most significant part of the hush house emission spectrum. Large amplitude sound pressure levels within a spectral range extending from just below to just above the audible threshold could result in impacts ranging from nuisance to hearing loss.
- (2) Vibration - vibrations induced in buildings in proximity to a hush house produced by infrasonic hush house emissions can be of sufficient magnitude to either interfere with functions within a building or threaten the structural integrity of the building. Furthermore, the impact of these vibrations on building occupants can include fatigue, annoyance or stress-induced illness.
- (3) Air Quality - impacts will focus on compliance with National Ambient Air Quality Standards for pollutants as well as ancillary requirements in California, Colorado and Florida. Compliance with opacity standards will also be addressed.

The above described issues will be addressed in terms of zones of influence where, within each issue, zones will be defined on the basis of the severity of the siting constraint imposed by the level of impact anticipated within that zone.

Potential mitigation measures which can serve to render siting constraints less restrictive which are identified within the course of this study will be described. During the scoping effort, one potentially significant mitigation measure has been identified which could serve to minimize or eliminate the hush house infrasonic emissions which have produced vibrations in facilities in the vicinity of hush houses. The technique is a modification of the flow of air drawn through the hush house walls and into the muffler tube. This flow modification method will serve to rapidly slow the fast moving engine exhaust gases. This method can be implemented without impacting the engine, without increasing the engine backpressure, and without modification of the hush house.

OAK RIDGE NATIONAL LABORATORY

OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37831

October 3, 1986

Mr. Roger Blevins
HQ AFLC/DEPR
Wright-Patterson Air Force Base, Ohio 454335001

Dear Roger

As per our telephone conversation of September 25, enclosed is a preliminary draft of our scoping document as well as a copy of the briefing I gave to General Ellis on September 17.

I will contact you following my return from the Burlington VT Air Guard Base to inform you our schedule for the field tests and to confirm a date for a status briefing. At this briefing we will be prepared to discuss options for ancillary studies directed towards mitigation.

Sincerely,

Alan Witten

AJW:mh

cc: C. Easterly
R. Miller
M. Swihart
R. Thoma

ATCH. 2

SUMMARY OF BRIEFING FOR GEN. ELLIS, SEPT. 17, 198

A Hush House (Fig. 1) is a hanger-like structure designed for noise suppression during extended aircraft engine diagnostic tests. The walls of the structure are composed of acoustic baffles which attenuate sound but admit air flow into the building to both provide cooling and prevent engine compressor stall. Exhaust gases exit the building via an augmentor (muffler) tube with the exhaust flow being deflected upward by a deflector ramp at the downstream end of the tube.

Figure 2 shows an F-4 aircraft installed in a Hush House for testing. Along with this configuration, tests can be performed in an engine-only mode with the engine mounted on a stand. There are currently approximately seventy Hush Houses in operation in this country and they have proven to be effective at noise suppression.

Oak Ridge National Laboratory's involvement with Hush Houses is result of problems encountered at several Hush Houses. Specifically, these problems involve significant vibrations induced in nearby buildings as a result of low frequency (sub audible) emissions from the Hush Houses. Our responsibility in this project is the evaluation of Hush House impacts as they relate to the siting of future Hush Houses as well as the siting of vibration sensitive facilities, such as avionics labs, at both current and future Hush House installations. The study will aid in the development of detailed Hush House siting criteria. To support this effort, we are collaborating with the Air Force Geophysics Laboratory in limited field studies directed towards characterizing low frequency Hush House emissions

as well as applied research to investigate the physical mechanisms which cause these low frequency emissions. Our findings to date include

- (i) low frequency acoustic emissions from Hush Houses are the rule rather than the exception,
- (ii) few problems have been reported because of the absence of sensitive receptors in proximity to existing Hush Houses,
- (iii) realignments to modern fighter aircraft are expected to cause many more problems because of the necessity for vibration-sensitive support facilities, and the origins of low frequency emissions from Hush Houses appears to be a result of a resonant mode of the Hush House structure driven by the aircraft engine exhaust flow.

Figure 3 illustrates what we believe to be the cause of the problem. Here you see the blue flame of the engine exhaust. This exhaust flow is at a high Reynold's number and consequently should behave like a turbulent jet. If this were the case the blue flame would quickly taper (narrow) with distance from the rear of the engine, rather than maintaining a uniform diameter as can be seen in this figure. This is because the energy in the exhaust flow which would go into the development of turbulence is preferentially-removed by acoustic Cherenkov radiation. Acoustic Cherenkov radiation is a result of the fact that the exhaust gas velocity is sonic with respect to the speed of sound at the temperature of the exhaust gas. Since this exhaust gas is quite hot it has a sound speed at least twice that of the surrounding air. Thus, the engine exhaust gas is moving at a speed which is supersonic with respect to the ambient air. Cherenkov radiation results whenever a particle stream or a fluid moves faster than the wave speed in the host medium. The resulting wavefront resembles a shock cone.

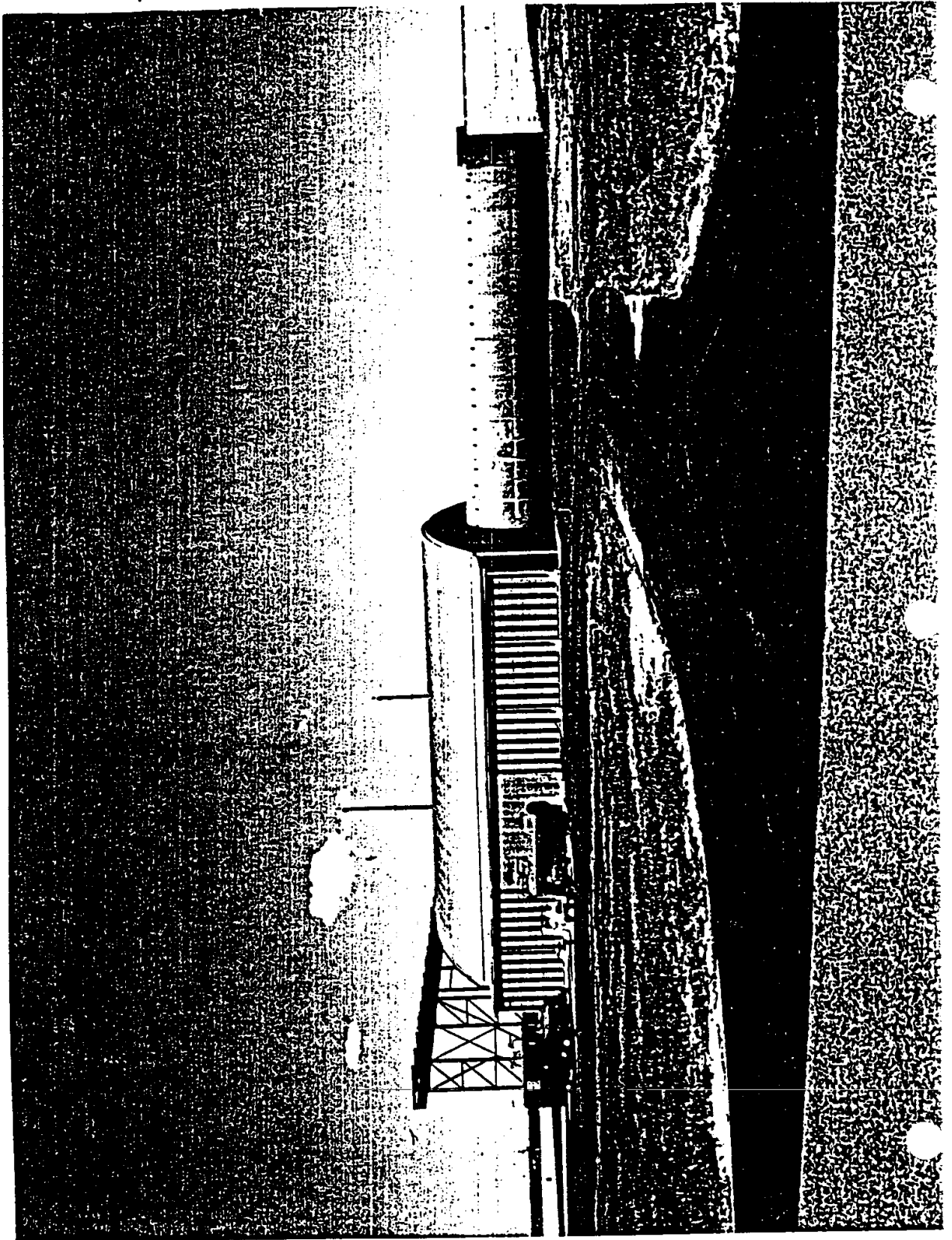
It is possible to calculate the frequency of acoustic Cherenkov radiation which depends on the engine exhaust velocity, exit diameter and exit temperature. For these parameters which are typical of fighter aircraft engines, the predicted Cherenkov radiation frequency is about 10 Hz which is comparable to the radiation frequency observed at Luke AFB.

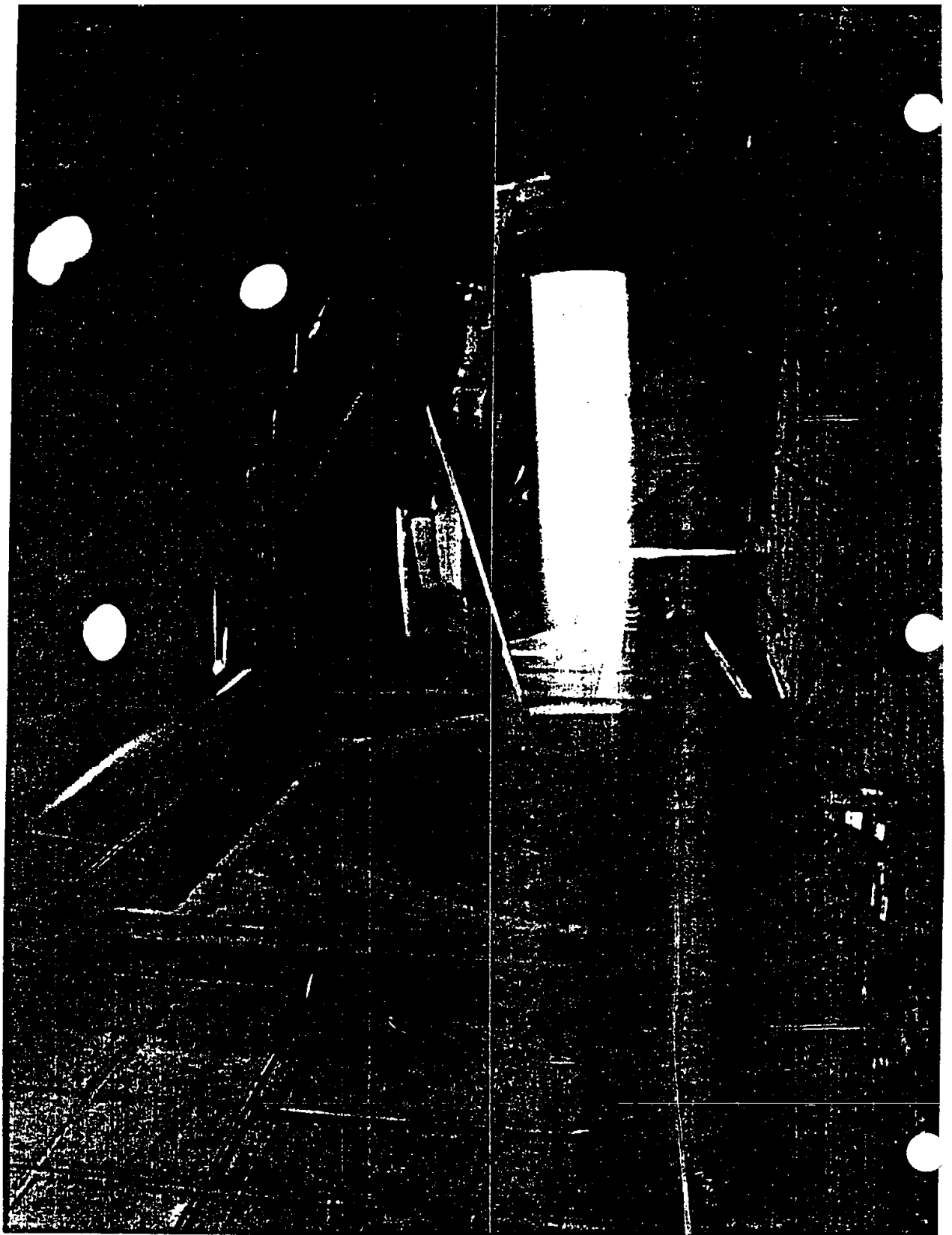
Enhanced coupling of this wave energy to the environment is believed to occur as a result of a resonance of the augmentor tube. Such a coupling will occur when the driving frequency (acoustic Cherenkov radiation) matches the natural (resonant) frequency of the structure. The fundamental mode (frequency) of the augmentor tube will be one in which the associated wavelength is equal to twice the length of the augmentor tube. For the elevated sound speed within the augmentor tube, this natural frequency has been calculated at approximately 10 Hz. Thus, it appears that augmentor tube is tuned to the acoustic Cherenkov radiation emitted from the engine exhaust, and that the augmentor tube is not functioning as a muffler but rather has become an organ pipe.

At this point, available vibroacoustic data at operating Hush Houses strongly supports the theory put forth above, however, insufficient data currently exists for absolute confirmation. If our belief proves correct, mitigation could be accomplished with a simple and inexpensive retrofit. The acoustic Cherenkov radiation is a stabilizing influence on the jet of exhaust gas. By providing a mechanism which promotes a hydrodynamic instability the stabilizing influence of the Cherenkov radiation will be negated. This would either substantially reduce the magnitude of vibrations or completely eliminate them. The exhaust jet could be destabilized by the superposition of a flow field which is known to render a laminar jet turbulent. The necessary air flow exists and is the entrained ambient air

drawn into the augmenter tube by the ejector pump action of the engine. Modifying this flow so that it has the proper characteristics to promote an instability would be accomplished by means of flowturning vanes mounted peripheral to the engine but not in contact with engine exhaust gas. The cost of fabrication and installation of these vanes could be as low as \$1000 per Hush House.







AFGL Technical Memorandum No. 112

AFGL HUSH HOUSE STUDY - LUKE AFB
PRELIMINARY RESULTS

by

James Battis
25 June 1965

Distribution of this document is limited. Other requests for this document may be addressed to AFGL/LWH, Hanscom AFB, MA 0173.

PREFACE

The AFGL Technical Memorandum Series is intended to make results of AFGL in-house scientific efforts rapidly available to specific groups and individuals known to have an immediate interest in the results obtained. Where appropriate, final results for the permanent record will be published later in the AFGL In-House Technical Report (TR) Series for wide distribution, including DTIC. A Technical Memorandum may not be referenced in the open literature; however, results presented therein may be referenced as "private communication" with the written consent of the originating office.

AFGL HUSH HOUSE STUDY - LUKE AFB

PRELIMINARY RESULTS

1.0 INTRODUCTION

In September and October Or 1984, AFGL -conducted a field study at Luke AFB to examine the vibration and acoustic emissions of a Hush House and the vibro -acoustic environment in Building S99 induced by Hush House operations. The occupants of Bldg 999 have complained of several vibrations and noise problems caused by Hush House engine testing. Because of these complaints, questions have been raised about the physical integrity of the structure and the environmental impact on the occupants of the building.

The primary intent of this study was to establish the feasibility of forecasting the vibro-acoustics produced by Hush House operations in nearby structures. These forecasts could then be used to aid in site selection for future Hush House construction. In addition, this study directly tests the conclusions drawn by previous investigators concerning the cause of the problems in Bldg 999.

2.0 RESULTS SUMMARY

Based on the preliminary analysis of the data taken during the Luke AFB field study, the following conclusions can be made:

- (1) To a first approximation, Hush House emissions, in the

far-field, can be modeled as a point pressure source in the neighborhood of augmentor tube exhaust box. It can be anticipated that, at near-field distances, a more complex source model might well be required to map Hush House emissions. At present, full analysis of the Luke Hush House source attributes is incomplete.

- (2) A key element of the forecast. scheme previously proposed by AFGL (J. Battis, Estimation of Structural Response to Ground Vibrations , presented at the Ground Run-up Suppressor Program Review, - 30-31 May, 19 84, HQ AFLC/DEP, Wright-Patterson AFB, Ohio) is found to be feasible. Prediction of the vibro -acoustic environment induced by Hush House operations should be realizable. Further studies are required to locate and define the Hush House source attributes. The consistency of these emissions at different sites and the importance of engine type, among other factors, has yet to be demonstrated. A well defined Hush House source model is essential to the forecast procedure.
- (3) For Bldg 999, the primary, although not exclusive driving force for vibrations is the infrasonic emissions from the Hush House. While seismic loads on the structure are also generated, either directly through the foundation of the Hush House or through acoustic coupling with the ground, their contribution to the observed problem not substantial' in this case . (While seismic precursors to the air path induced motions were detected,

their amplitudes were small, particularly for the upper floors.) This finding is essentially in agreement with prior studies of the Luke problem.

- (4) The orientation of Bldg 999 relative to the Hush House is a significant factor in determining the response and interior vibro -acoustics. This fact will be generally true of buildings elsewhere. Any attempts to describe the impact of Hush House operations in surrounding buildings solely on the basis of range from the Hush House will be materially corrupted by site specific responses.

3.0 The EXPERIMENTAL PLAN

The field study conducted at Luke AFB was carried out in three phases. First, seismometers and pressure transducers were positioned in Bldg 999 to record the vibration and acoustic disturbances in the structure due to Hush House operations. During this phase of the study, observations were made with the Hush House testing F -100 engines at military power and with afterburner. The locations of the sensors during the first phase effort are shown in Figure 1. It is worth noting that throughout each phase of the study, one pressure transducer was located approximately half way between the Hush House and Bldg 993 as a reference observation.

The second phase of the study called for the measurement of motion and acoustic responses in Bldg 999 due to a series of small, elevated explosive detonations. The locations of the

shot points used for this phase of the experiment are shown in Figure 2. These responses form part of the basic data set required to make the forecasts. Given the vibration or acoustic responses generated by a known source, the motions or acoustics produced by a second, like class source over the same path, can be estimated.

Finally, the third phase of the study consisted of locating and defining the source characteristics of the Luke Hush House, itself. In this case, two sensor arrays were set up on the aircraft apron between the Hush House and Bldg 999. Again, Hush House emissions were measured by these arrays during the testin5 of F-100 engines under military power and with afterburner. Analysis of these data is incomplete.

4.0 OBSERVED DATA

Figure 3 displays sample time histories of data recorded at Bldg 999 during Hush House operations. For these particular records, an F -100 engine with afterburner was being tested in the Hush House. The data shown in this figure are representative of the other sensor locations and of the data collected during other Hush House test runs with engines in afterburner. Channels 2 and 7 are the outputs of a seismometer located on the roof and the foundation footing, respectively, at Column Line "L" on the southeast face of Bldg 999. Channel 2 is the horizontal motion recorded along the short (NW-SE) axis of the structure while Channel 7 is the vertical motion record for the footing. Channels 12 and 15 are acoustic

signals recorded at the southwest end Or the second floor corridor and at the halfway point between the Hush House and Bldg 999, respectively.

Motion levels observed on the *floor* of Bldg 999 have the largest amplitudes while those at the foundation slab level have the lowest levels. Based on the mid *-band* sensitivity of the recording system, a peak velocity of 0.5 mm/sec was recorded at the door to the Deputy Commander's office. In all cases the motion levels are below typical thresholds for structural damage due to vibration. However, it should be noted that the sensor locations used in this study were not chosen to maximize the expected levels of observed motions.

Figure 4 (a) shows the output from the same set of instruments to the known acoustic source, a small charge detonation, located somewhat east of the exhaust box of the Hush House augmentor tube at Shot Point A. The acoustic record on Channel 16 shows the pressure loading from this shot is complicated by a reflected signal that is probably coming off the exhaust box or the Hush house. The reflection is indicated on the figure by an arrow. A source pressure record of an explosion would have only one short transient rather than the multiple transients found on this record. The extended vibro *-acoustic* responses in Bldg 999 measures the sensitive of this structure to acoustic and acoustic coupled seismic loading. It is noted that the ground path precursors are small particularly for the upper building levels.

The sensitivity at Bldg 999 responses to source orientation

is demonstrated by the explosion tests. In Figure 4, measured response at each of the four sensor locations are shown for the three shot positions. The acoustic response for Channel 16 is much the same for each shot. This is expected as the sensor is located in an open, flat field and the site response is governed solely by the range or the source and acoustic propagation in the open atmosphere which remained essentially constant throughout the explosive tests. For the structure, however, significant differences, in terms of amplitude and frequency content, are noted in the building responses to the three source locations. Only a modest change in azimuth was covered in these tests, but it is clear that the relative orientation of the source with Bldg 999 is critical in defining the structural responses. Distance -to the Hush House is an incomplete criteria for forecasting the vibro -acoustic environment in Bldg 999, or more generally, for any structure.

5.0 Forecast Estimates

The forecast procedure used here by AFGL is represented by the equation:

$$u'_i{}^{HH}(t) = p_{16}{}^{HH}(t) * w(t)$$

where $u'_i{}^{HH}(t)$ is the forecast Hush -House induced -motion or pressure time history for some given location, designated i , $p_{16}{}^{HH}(t)$ is the observed Hush House emission measured at Channel 10, and $w(t)$ is a linear operator connecting the explosion pressures at Channel 16 with the motion or pressure responses to the explosion at location Bldg 999. The

Figure 1 - Sensor locations for Bldg 999, Luke AFB.

Figure 2 - Relative locations of hush House and Bldg 999
at Luke AFB and the locations of the three shot
points and acoustic sensor Channel 16.

linear operator, $w(t)$, is defined as

$$w(t) = p_{16}^E(t) * [u_i^E(t)]^{-1}$$

where $p_{16}^E(t)$ is the pressure response recorded at Channel 16 due to the explosion and $u_i^E(t)$ is the motion or pressure response recorded at location i due to the explosion. It should be noted that $*$ denotes the convolution operation and further, the inverse of a time series is defined through the fourier transformation of the signal.

AFGL has not completed the analysis of the Hush House acoustic emissions. This effort is required to develop an equivalent Luke Hush House source model that can be used in a complete forecast scheme. However, the class source model has been tested on the basis of the acoustic signals recorded by the pressure sensor at Channel 16 with points on and in Bldg 999. This finding is an essential step in making forecasts using a site insensitive source.

The procedure to compensate for site sensitive responses to Hush House operations is tested for the locations of Channels 7 and 12. In Figure 5, the forecasted disturbances for each channel is presented along with a corresponding sample of the observed data from the same location. It is noted that the characteristics, such as peak amplitude and general frequency content, of each observed data trace is well reproduced in the forecasted trace.

A second test of the forecasted; is made by comparing power spectra of the observed and forecast signals for the F-100 engine in afterburner. Spectra for each of these channels are

shown in Figures 6 and 7. In the measurement pass band, the forecasted and observed spectra are quite similar. The forecast succeeds in compensating for the site peculiar responses encountered at Luke AFB. Given the fact that the Hush House and the shot were not collocated, it is felt that the forecasted motions and pressures are excellent representations of the true values. Finally, Figure 8 shows the observed and forecast motion spectra for Channel 12 with an F-100 engine operating in military power. Again, the observed and forecasted motions are in good agreement.

6.0 SUMMARY

In summary, it has been shown that knowledge of a structure's response to an explosion at a given location can be used to accurately estimate the Hush House induced disturbance at that location. Development of the Hush House source model is now the logical next step to produce a robust forecasting tool. The correspondence obtained here is sufficient to believe that a site insensitive source model can be defined to forecast the vibro-acoustic environment surrounding Hush House operations.

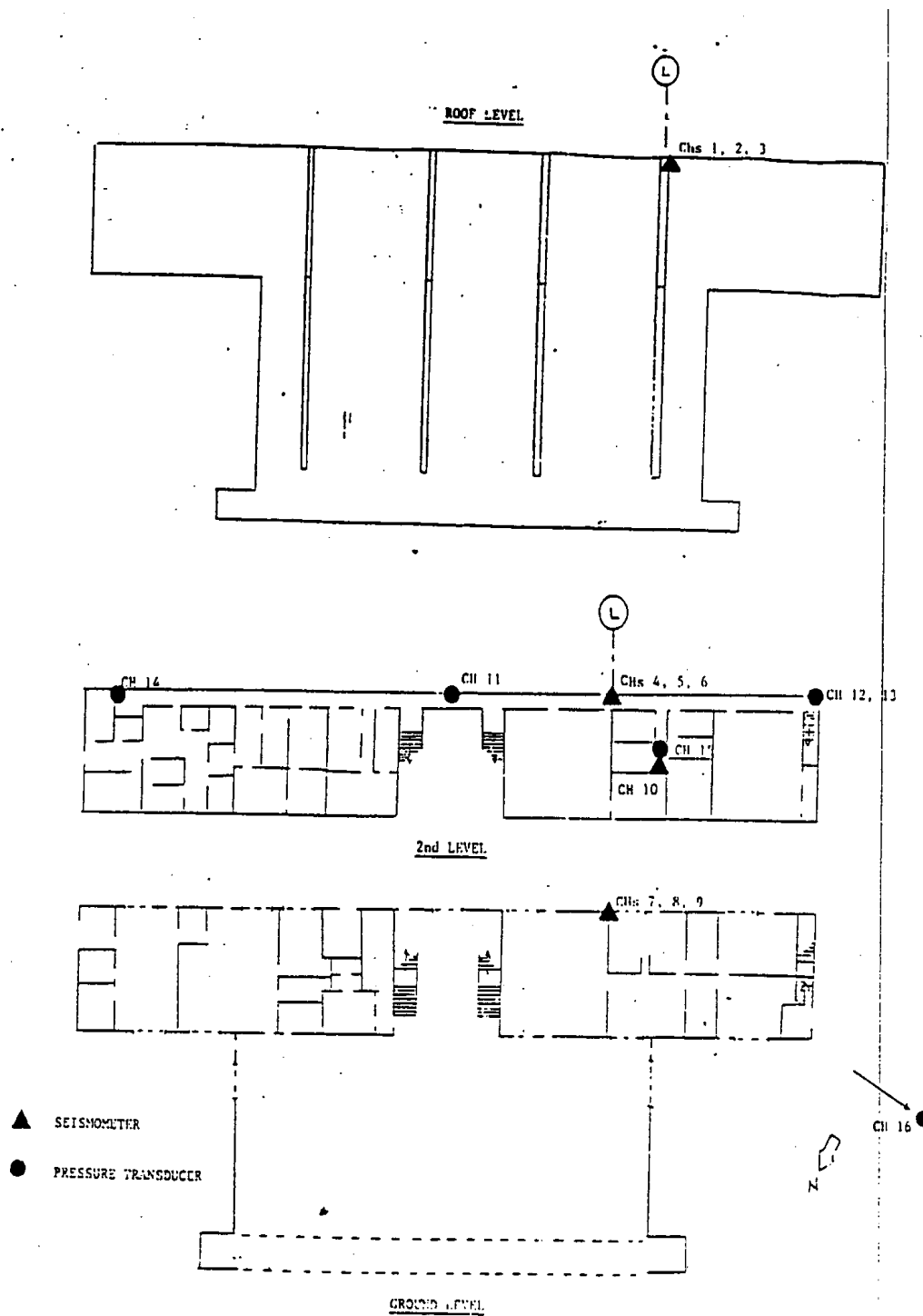


Figure 1 - Sensor locations for Bldg 999, Luke AFB.

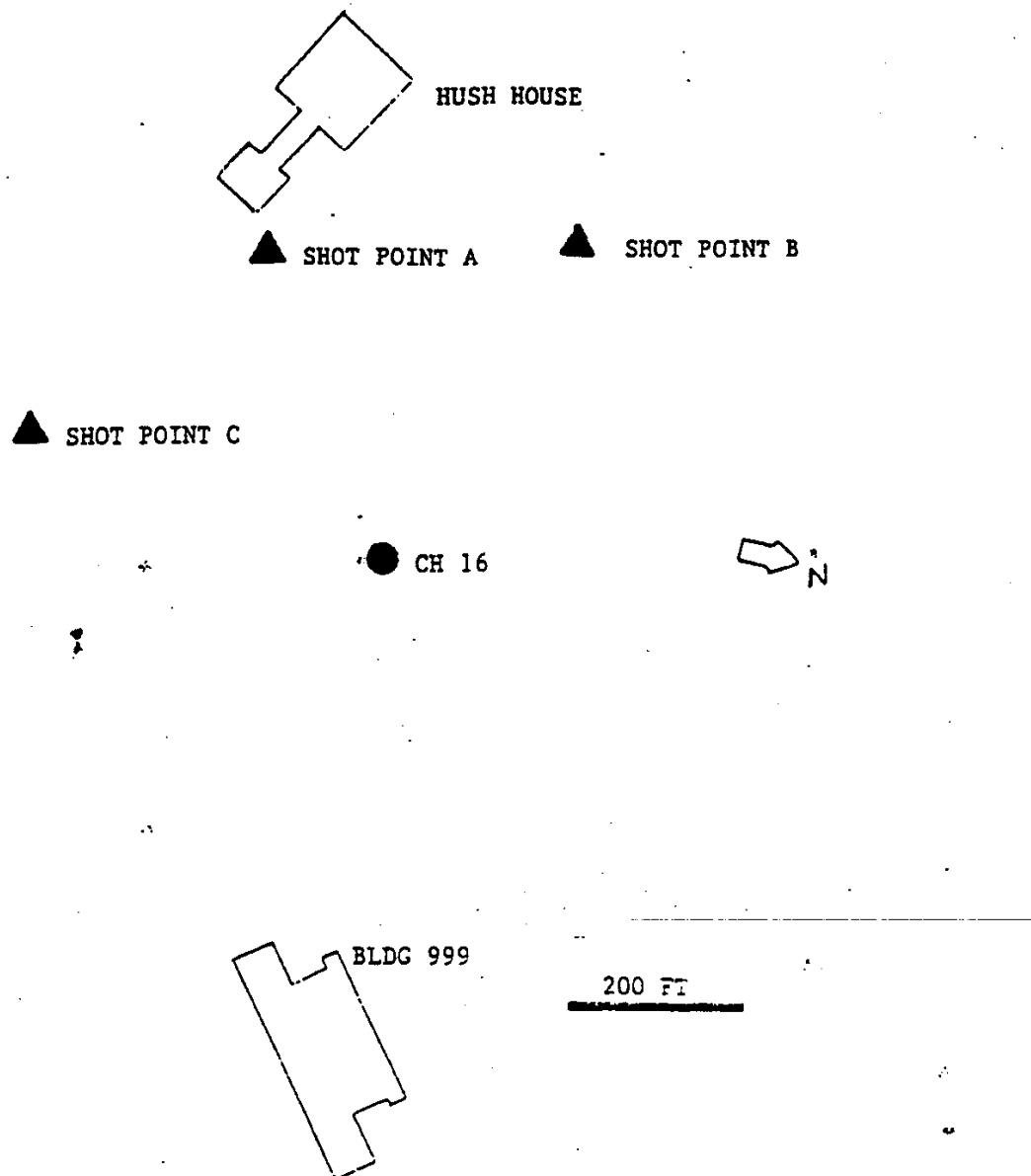


Figure 2 - Relative locations of hush House and Bldg 999 at Luke AFB and the locations of the three shot points and acoustic sensor Channel 16.

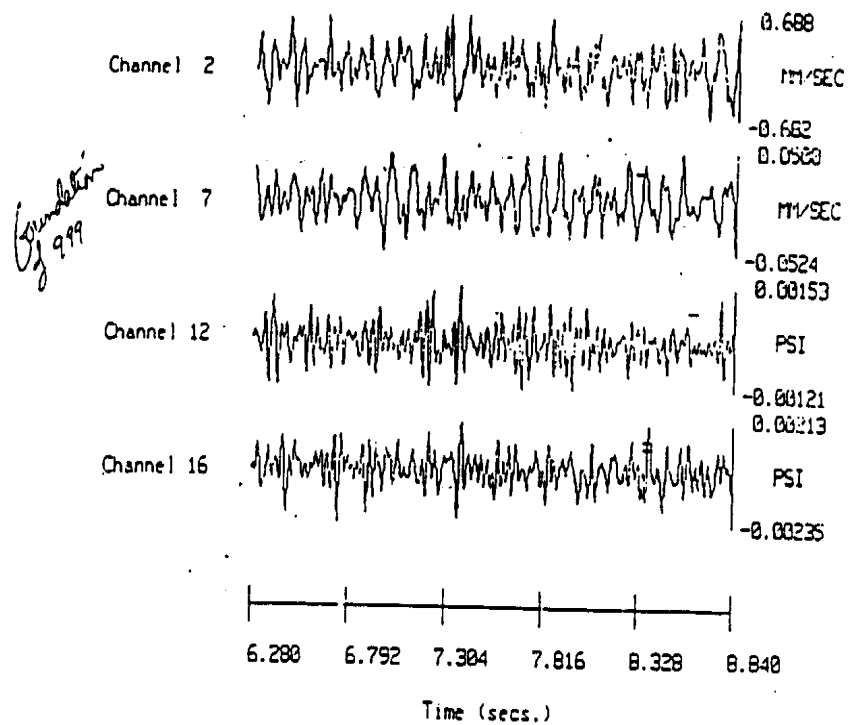


Figure 3 - Observed sample time histories for seismic and pressure sensors located in Bldg 999. Also shown is the observed acoustic record for Channel 16. All traces for an F-100 engine with afterburner in the Hush House.

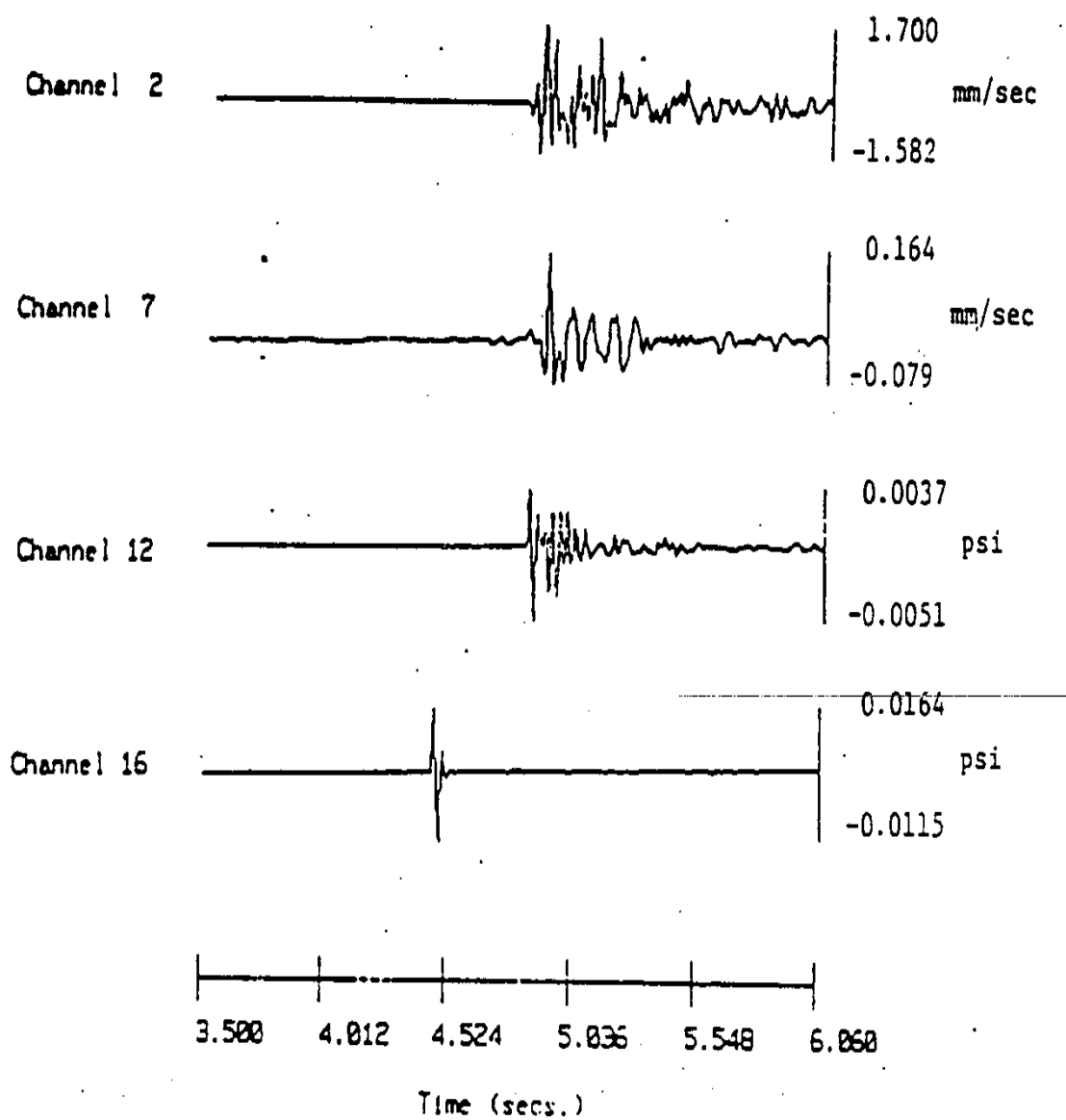


Figure 4 - (b) Responses for Bldg 999 locations and Channel 16 to charge detonations at Shot Point B shown in Figure 2.

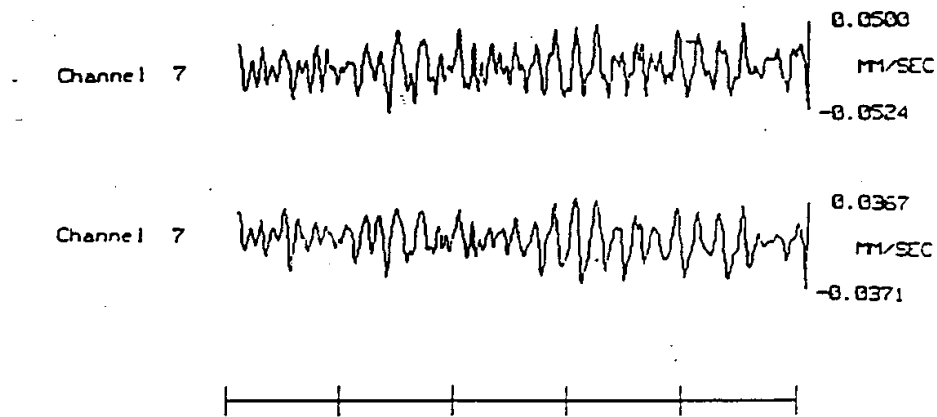


Figure 5 - (a) Observed (upper) and forecast (lower) acoustics for the NW end of the second floor corridor of Bldg 999 for an F-100 engine in afterburner.

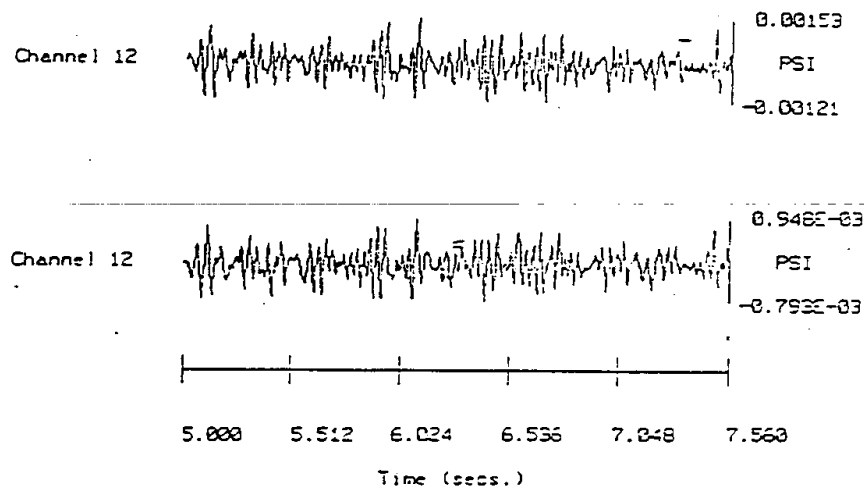


Figure 5 - (b) Observed (upper) and forecast (lower) motion spectra for the SE-NW horizontal component on the roof of Bldg 999 for an F-100 engine in afterburner.

Figure 5 - Observed (upper) and forecast (lower) motion spectra for the SE-NW horizontal component on the roof of Bldg 999 for an F-100 engine in afterburner.

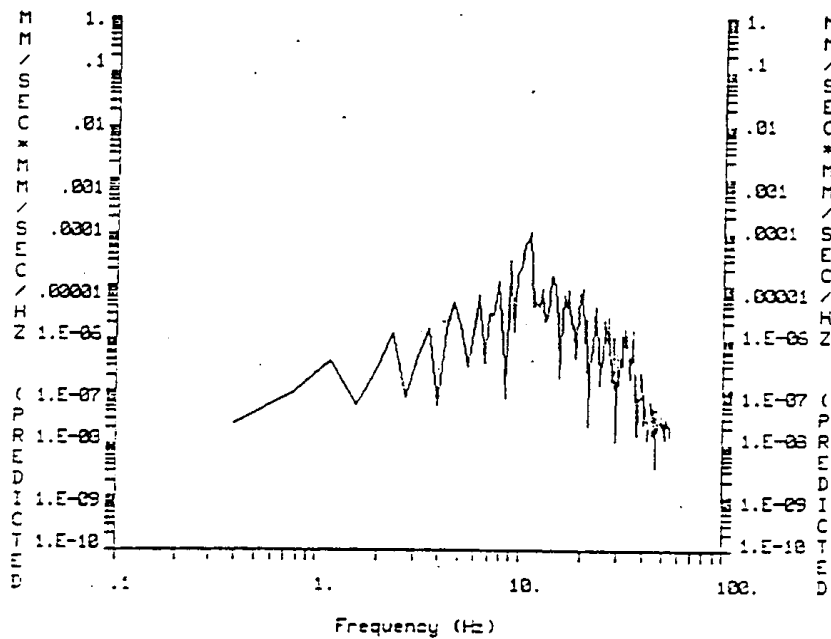
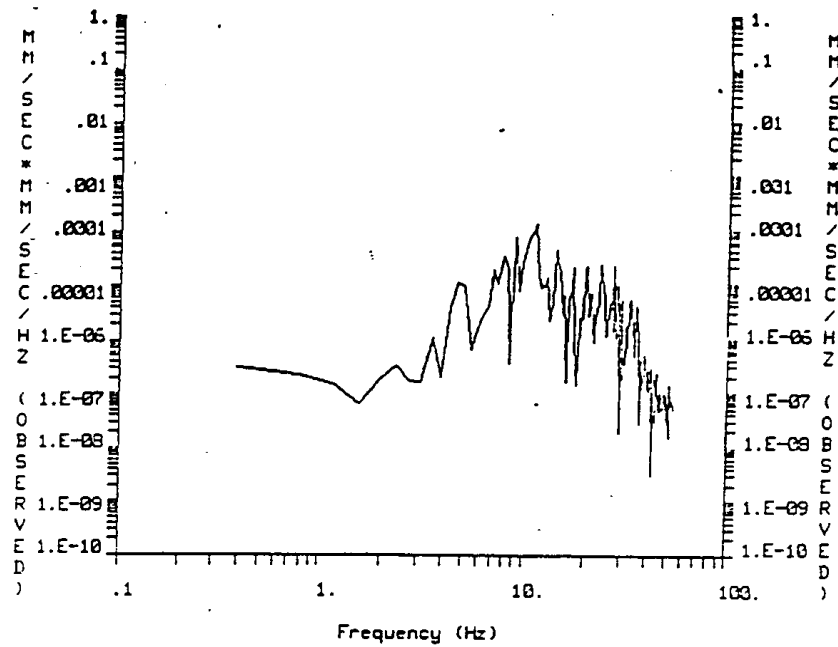


Figure 6 - Observed (upper) and forecast (lower) motion spectra for the SE-NW horizontal component on the roof of Bldg 999 for an F-1000 engine in afterburner

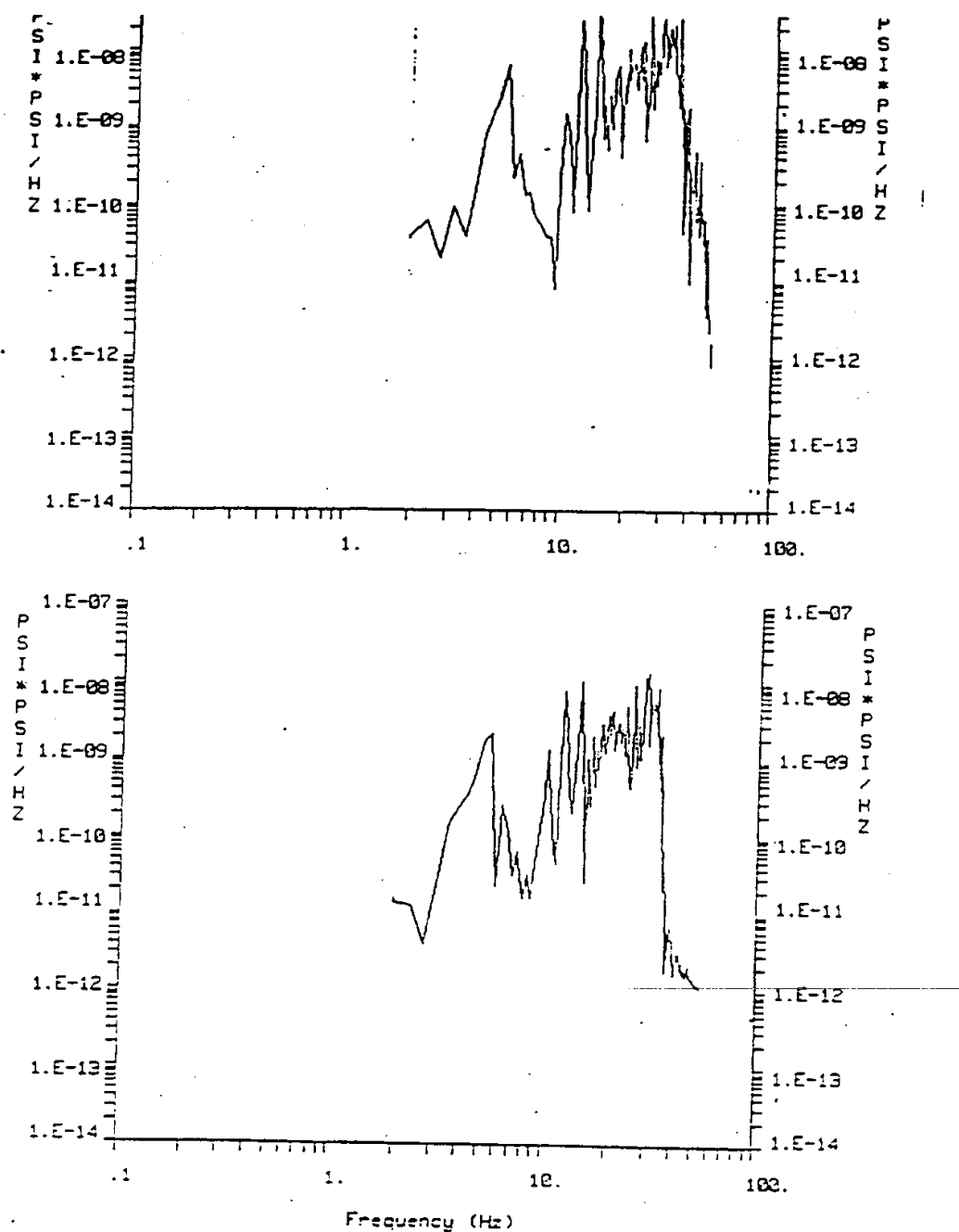


Figure 7 - Observed (upper) and forecast (lower) acoustic spectra at the NW end of the second floor corridor of Bldg 999 for an F-100 engine in afterburner.

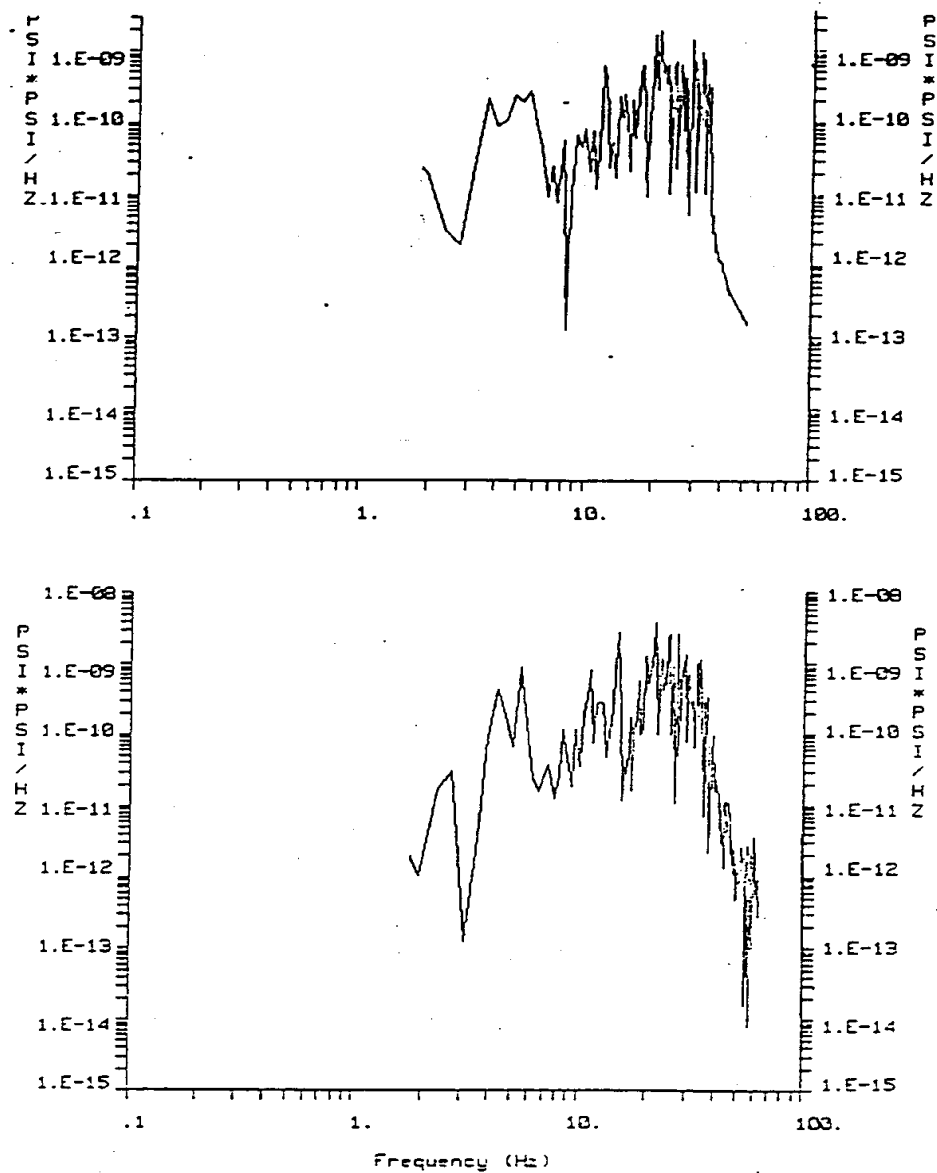


Figure 8 - Observed (upper) and forecast (lower) acoustic

Figure 8 - Observed (upper) and forecast (lower) acoustic spectra at the NW end of the second floor corridor of Bldg 999 for an F-100 engine in military power.